UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

A PALEOMAGNETIC AND PETROGRAPHIC ANALYSIS OF UNCONFORMITY SURFACES IN NEVADA AND MISSOURI: POSSIBLE IMPLICATIONS FOR PALEOWEATHERING PROCESSES

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

BRANDON MICHAEL SPENCER
Norman, Oklahoma
2017

A PALEOMAGNETIC AND PETROGRAPHIC ANALYSIS OF UNCONFORMITY SURFACES IN NEVADA AND MISSOURI: POSSIBLE IMPLICATIONS FOR PALEOWEATHERING PROCESSES

A THESIS APPROVED FOR THE
CONOCOPHILLIPS SCHOOL OF GEOLOGY AND GEOPHYSICS

BY

____
Dr. Shannon Dulin, Chair

____
Dr. R. Douglas Elmore

____
Dr. Gerilyn Soreghan

Acknowledgements

Many thanks go to my advisor, Shannon Dulin, for her friendship, guidance, and endless laughs over the last few years. Thanks also to my other committee members, Doug Elmore and Lynn Soreghan, who have been more than patient with me while fighting through equipment issues and life obstacles. The influence of all three of these fine people will weigh on me as I work further towards my academic and professional goals.

I'd like to thank Gayln, a good field partner/sample collector/mood lightener/aspiring beer connoisseur and a great friend. Thanks to Jennifer, Jon, Gerry, and Alyssa for their discussions and friendly ears during my gripe sessions. Melissa Bennett was the MVP during my last days in the lab—thanks for sticking around and helping with IRM processing. Thanks to Chrissy for help with editing and proofing. Undergraduates who helped in the magnetometer lab, I appreciate your help. Thanks to Frank for inspiring vigorous conversation on the magnetometer maintenance highway. Thanks go to Ashlyn, who kept me on track as an undergraduate here with her enthusiasm for doing it the right way.

Finally, I cannot express enough appreciation to my wife, Ruth, and my kids, Cooper, Emmalin, and Alissa, for their unending love and patience; for the late nights; for the long weeks at field camp; for the sampling and field trips; and for everything yet to come.

Table of Contents

Acknowledgements iv

List of Tables vii

List of Figures viii

Abstract x

Introduction 1

Chapter 1: Paleoweathering analysis of the Great Unconformity at Frenchman Mountain, Nevada 3

Geologic Background and Previous Work 3

Methods 11

Results and Interpretations 13

Paleomagnetic Results 13

Rock Magnetic Results 24

Petrographic Results 27

Discussion 30

Vishnu Group 30

Tapeats Sandstone 34

Conclusions 35

References 37

Chapter 2: Paleomagnetic and Petrographic Analysis of an Unconformity Surface in the Butler Hill Caldera, SE Missouri 43

Geologic Background and Previous Work 43

Methods 49

Results and Interpretations 52

Paleomagnetic Results..52

Rock Magnetic Results..61

Petrographic Results...64

Discussion..70

Butler Hill Granite and Grassy Mountain Ignimbrite..............................70

Lamotte Sandstone 73

Conclusions 75

References 78

Conclusions 82

List of Tables

Chapter 1

Table 1. Paleomagnetic data from Vishnu and Tapeats rocks..................................18

Chapter 2

Table 1. Paleomagnetic data from Missouri igneous and sedimentary rocks 54

List of Figures

Chapter 1

Figure 1. Simplified geologic map of FMB 6

Figure 2. Image of unconformity surface at Frenchman Mountain.............................6

Figure 3. Las Vegas NE geologic map and study area..8

Figure 4. Paleomagnetic ChRM of Vishnu 14

Figure 5. AF demagnetization results of Vishnu...16

Figure 6. Equal area net of high temperature component in Vishnu.........................17

Figure 7. Paleomagnetic results of Tapeats sandstones..20

Figure 8. Equal area net of Tapeats directions 21

Figure 9. Phanerozoic apparent polar wander path with NV poles...........................22

Figure 10. Proterozoic apparent polar wander path with NV poles 23

Figure 11. IRM results for Vishnu 25

Figure 12. IRM results for Tapeats...26

Figure 13. Hematite occurrence in optical and SEM analyses..................................28

Figure 14. SEM and optical images of albitization in Vishnu rocks.........................29

Figure 15. SEM image of hematite replacement of K-feldspar................................29

Chapter 2

Figure 1. Geologic map of southeastern Missouri and St. Francois Mountains........43

Figure 2. Geologic map of Butler Hill Caldera 44

Figure 3. Image of unconformity at Grassy Mountain Ignimbrite roadcut 46

Figure 4. Map of paleomagnetic sampling sites..51

Figure 5. Paleomagnetic results of igneous rocks and ChRM..................................53

Figure 6. Equal area nets of all Missouri paleomagnetic directions..........................56

Figure 7. Paleomagnetic results of Lamotte sandstones..57

Figure 8. Conglomerate test results for Lamotte basal boulder bed..........................58

Figure 9. Phanerozoic apparent polar wander path with MO pole............................59

Figure 10. Proterozoic apparent polar wander path with MO pole...........................60

Figure 11. IRM results for Grassy Mountain Ignimbrite..62

Figure 12. IRM results for Butler Hill Granite...62

Figure 13. IRM results for Lamotte sandstones...63

Figure 14. SEM and optical images of Butler Hill Granite.......................................65

Figure 15. Optical petrography of hematite in Butler Hill Granite...........................66

Figure 16. SEM and optical images of Grassy Mountain Ignimbrite........................67

Figure 17. Optical petrography of Lamotte sandstones..68

Figure 18. Photomicrographs of graptolites within Lamotte-Bonneterre.................69

Abstract

Paleomagnetic dating has proven to be a valuable tool in dating geologically significant events such as timing of deposition, deformation, or diagenesis. When combined with petrographic methods and field relationships, we can often accurately constrain the timing of these events and elucidate a more complete picture of the geologic history of a formation or region.

This study combines paleomagnetic, petrographic, and rock magnetic study of crystalline basement rocks, their upper bounding unconformity, and overlying sedimentary cover in two locations in Nevada and Missouri. First, the unconformity between the Proterozoic Vishnu Group granites and schists and overlying Cambrian Tapeats Sandstone in southern Nevada represent almost one billion years of missing rock record. Prior to deposition of the Tapeats, it is likely that the Vishnu underwent subaerial exposure for an extended period of time and may have recorded surficial processes caused by the penetration of supergene fluids enriched in weathered material. Paleomagnetic and rock magnetic analysis of Vishnu and Tapeats specimens revealed stable ancient magnetizations in both lithologies. A characteristic remanent magnetization held primarily in magnetite in rocks from four Vishnu sites exhibits north to northeasterly declinations and moderately steep up inclinations and yields a paleopole at 16.3°S latitude and 129.9°W longitude, which falls near the Mesoproterozoic portion of the apparent polar wander path for North America. This magnetization was likely acquired during the end stages of metamorphism in the Mesoproterozoic and is interpreted as a thermoremanent

magnetization acquired during cooling following metamorphism. Petrographic analysis of Vishnu specimens reveals the presence of titanomagnetite as an igneous accessory mineral in the rocks. Magnetizations in the Tapeats Sandstone, although stable, contain scattered directions and are interpreted as the product of time-progressive acquisition of magnetizations in hematite grains acquired over a long period of time. Unfavorable local climatic conditions or subsequently eroded sedimentary units may have prevented the basement from acquiring or preserving a magnetization in hematite during exposure in the late Proterozoic.

The second part of this work evaluates the Proterozoic Butler Hill Granite and Grassy Mountain Ignimbrite and overlying Cambrian Lamotte Sandstone of the St. Francois Mountains in southeastern Missouri. Like the unconformity surface in Nevada, the contact between basement and sedimentary cover in Missouri represents nearly one billion years of time and is known to contain variable topographic relief on the surface of the Proterozoic basement. Paleomagnetic directions in the igneous rocks are westerly and moderately steep down, corresponding to a paleopole of 3.4°S latitude and 145.1°W longitude, agreeing with a previously published primary Mesoproterozoic (1.476 ± 16 Ma) magnetization. This is interpreted as a primary magnetization held predominantly in magnetite acquired during emplacement and eruption of the rocks. Petrographic and rock magnetic analysis confirms magnetite as the magnetic carrier. The Lamotte Sandstone contains a stable ancient magnetization with southeasterly declinations and moderate down inclinations, corresponding to a paleopole of 14.7°N latitude and 126°W longitude, on the Silurian portion of the apparent polar wander path for North America, with an error ellipse that overlaps the Mississippian. This is interpreted as a chemical remanent magnetization held in magnetite acquired during the late Devonian to early Mississippian from subsurface fluid flow in the St. Francois aquifer during movement of Fe-rich ore-forming hydrothermal fluids. The silica-rich, impermeable Grassy Mountain Ignimbrite likely served as a protective seal for the crystalline basement and prevented penetration of supergene or orogenic fluids into the upper basement rocks, preserving the primary magnetization held in the ignimbrite and the Butler Hill Granite.

Introduction

Understanding paleoclimatic and ancient surficial processes and conditions is an important aspect of understanding modern climate change and surface geologic processes. Atmospheric carbon dioxide, one of the gases considered to be a major contributor to warming, is buffered by the chemical weathering of silicate rocks. This weathering induces any number of mineralogical changes in the rock, including the possible albitization of alkali feldspars and precipitation of authigenic hematite (e.g. Creer, 1968; Parcerisa et al., 2010; Dulin, 2014). Paleomagnetic dating of a magnetic remanence held in hematite can constrain the timing of hematite precipitation, possibly indicating timing of subaerial exposure and/or exposure to supergene meteoric fluids (e.g. Ricordel et al., 2007; Dulin, 2014). When combined with petrographic and rock magnetic analyses, we can gain a better understanding of the processes that acted on the rock during exposure to atmospheric conditions and chemical weathering.

This study aims to determine the presence and timing of hematite precipitation and/or albitization near two unconformity surfaces, further exploring the mechanisms of hematite precipitation and albitization previously described by Creer (1968), Ricordel et al. (2007), Parcerisa et al. (2010), Dulin (2014), and others. We present paleomagnetic, petrographic, and rock magnetic results from unconformity surfaces that represent nearly one billion years of missing time. Crystalline basement rocks and their overlying sedimentary cover from two different locations were chosen for analysis based on the likelihood that the crystalline basement rocks underwent subaerial exposure prior to marine transgression in the latest Proterozoic to early Cambrian. The Proterozoic Vishnu-equivalent igneous and metamorphic rocks and overlying Lower to Middle Cambrian Tapeats Sandstone at Frenchman Mountain, Nevada, form a well-studied sequence that crops out in the Grand Canyon and exhibits a well-exposed transition from the basement to the Paleozoic section. In the St. Francois Mountains region in southeastern Missouri, the Proterozoic Butler Hill Granite and Grassy Mountain Ignimbrite are both overlain by the Upper Cambrian Lamotte sandstone. This area is known to represent a paleotopographic high during the Late Proterozoic. Both sites provide opportunity to gather information about a significant unconformity surface and may give insight into the effects of paleoweathering conditions over geologic time. The similar age of the unconformities and likelihood of similar surface processes during exposure make the two locations comparable for the purposes of this study.

Chapter 1: Paleoweathering analysis of the Great Unconformity at Frenchman Mountain, Nevada

GEOLOGIC BACKGROUND AND PREVIOUS WORK

The Late Proterozoic is a time that is believed to represent a transition from a very cold global climate to a decidedly warmer one (e.g. Harland, 2007; Williams et al., 2016). In general, the shift from icehouse to greenhouse conditions would be expected to lead to wetter, warmer climates and, in turn, intensified weathering of exposed and near-surface rocks. Supergene fluids enriched in weathered material have been suggested to result in the precipitation of hematite in the upper portions of the underlying rock and acquisition of a magnetic remanence during the time of surface or near-surface exposure (Creer, 1968; Ricordel et al., 2007; Parcerisa et al., 2010; Hamilton et al., 2014; Dulin, 2014). Creer (1968) stated that the presence of Late Paleozoic remagnetizations in low-paleolatitude rocks, coupled with the absence of such remagnetizations in high paleolatitude rocks, indicated that warmer, wetter climates and increased weathering rates were responsible for those remagnetizations (1968).

The precipitation of hematite is commonly accompanied by the reddening of the host rocks. Unconformity surfaces with reddened igneous or metamorphic basement rocks overlain by sedimentary rocks have been studied by several authors. Parnell et al. (2000) and Dulin (2014) found Late Permian magnetizations in hematite in the Dalradian supergroup in Scotland, and Hamilton et al. (2014) found Permian magnetizations in reddened basement rocks in Oklahoma. In mainland

Europe, Ricordel et al. (2007) and Franke et al. (2010) found Permo-Triassic magnetizations residing in hematite in multiple locations, which they attributed to the penetration of weathering fluids through the sedimentary cover and into fractures in the crystalline basement. Diminishing presence of a magnetic remanence from surface exposure to deeper portions of the basement rock (Franke et al., 2010; Hamilton et al., 2014) support the theory of a top-down permeation of fluids.

Penetration of meteoric fluids into exposed silicate rocks does not necessarily result in the acquisition of a stable magnetic remanence in hematite. Dulin (2014) found scattered or unstable magnetizations in rocks from basement unconformity surfaces in Unaweep Canyon and Byers Canyon in Colorado. However, reddening was still present, indicating that hematite precipitation did occur, likely due to permeation of supergene fluids. The lack of stable magnetizations in these rocks possibly reflects localized climatic (Gutierrez, 2005) or tectonic factors, such as atmospheric $p\mathrm{CO_2}$, temperature, or elevation (Riebe et al., 2004; Dulin, 2014). These observations indicate that the conditions necessary for hematite precipitation and preservation of an acquired remanence may not have been widespread throughout Pangea, but may have been controlled by local factors.

Vishnu Group granites and schists and age-equivalent suites have been studied for many decades, mostly due to their presence and exposure as the oldest rocks visible in the Grand Canyon. Geochemical, structural, and petrographic work (e.g. Brown et al., 1979; Clark et al., 1979; Karlstrom et al., 2012) has been completed on many locations to determine the age, structure, and history of the rocks. Likewise, the Tapeats Sandstone has also undergone a significant amount of study in the Grand Canyon and other parts of the southwest (e.g. Burgert, 1972; Sears, 1973; Kennedy et al., 1996; Chadwick et al., 1998). Geo- and thermochronological studies, petrography, and abundant field work have helped to shed light on the provenance and transgressive marine deposition of the Tapeats following the breakup of Rodinia (Hereford, 1977; Chadwick et al., 1998)

In southern Nevada, the Tapeats and Vishnu-equivalent rocks have also been researched, albeit to a lesser extent than in the Grand Canyon. Their equatorial latitude during the Late Precambrian (post-Cryogenian) suggests that chemical and mechanical denudation would have been more intense there than in most other locations during that timeframe due to higher temperatures and precipitation rates (Gislason et al., 2009). With the planet's climate swing from "snowball" conditions in the post-Cryogenian (Harland, 2007) to greenhouse conditions, any rocks exposed at the surface, especially at equatorial latitudes, would likely have been subjected to intense weathering. The silicate basement rocks at Frenchman Mountain, Nevada (Figs. 1 and 2), correlate with the Vishnu group (Rowland, 1987) and would have provided a ready source of iron (4-11 wt%; Clark, 1979 and Brown et al. 1979) for oxidation upon weathering, resulting in precipitation of hematite in the upper parts of the exposed basement.

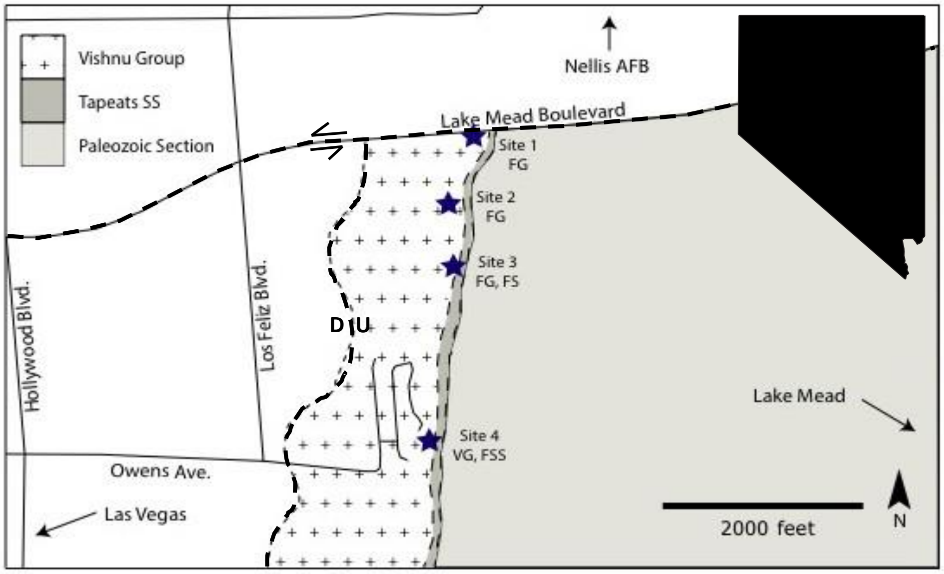


Figure 1 - Simplified geologic map of the western exposure of the Frenchman Mountain Block (FMB) northeast of Las Vegas, NV. Stars indicate sampling locations, with initials of site names next to stars. Inset map of Nevada shows approximate map area in white. Fault block is bounded approximately by the western border of the Proterozoic exposure (Frenchman Fault) and Lake Mead Boulevard (Boulevard Fault) to the north.

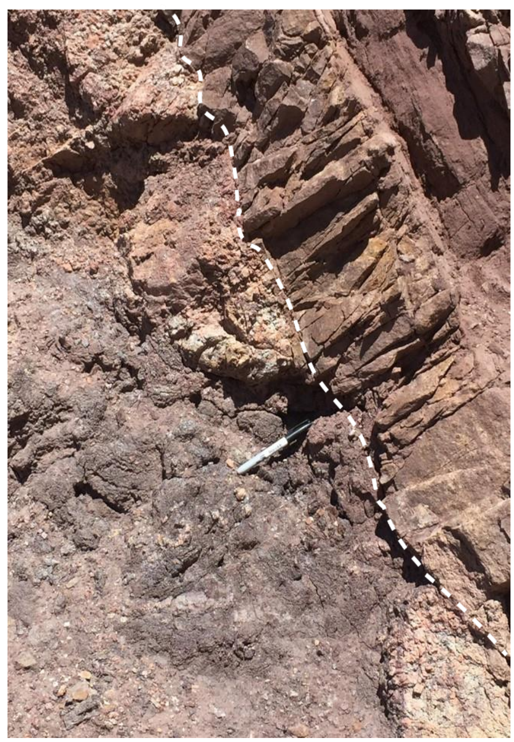


Figure 2 - Unconformity surface along the FMB near Las Vegas. Proterozoic Vishnu group rocks left of the dashed unconformity, Cambrian Tapeats sandstone on the right.

Previously, samples of Tapeats Sandstone from the Frenchman Mountain Block (FMB) northeast of Las Vegas were subjected to paleomagnetic study in hopes of better understanding the structure of the Colorado Plateau and the Cordilleran miogeocline (Gillett, 1982). These samples were interpreted to contain stable but random remanent magnetizations held in hematite (Gillett, 1982). Gillett interpreted the random directions to be a result of remanence acquired over time through diagenetic processes, and therefore did not attribute the magnetization to any single event (1982). No paleomagnetic work on the Vishnu Group at Frenchman Mountain has been published. However, a preliminary sampling trip showed an apparent stable Cambrian remanence in the restite at Frenchman Mountain and therefore warranted additional study.

Paleomagnetic work in the area of Las Vegas requires careful consideration of the structural/tectonic history of the region. The FMB is located in the Central Basin and Range (CBR) province and is dominated by approximately north-south striking, westward dipping normal faults formed during Cenozoic extension. The resulting structure consists of deep listric faults with eastward dipping fault blocks of Proterozoic basement and Paleozoic to Cenozoic strata (Fig. 3). Prior to Cenozoic CBR extension, strata in present-day southern Nevada experienced deformation from numerous orogenic events; the Sevier, Sonoma, Laramide, and Nevadan orogenies. The degree of influence these events had at Frenchman Mountain is not evident, but CBR extension has resulted in approximately 80 km of westward translation of the FMB (Rowland et al., 1990; Anderson, 1998; Eaton,

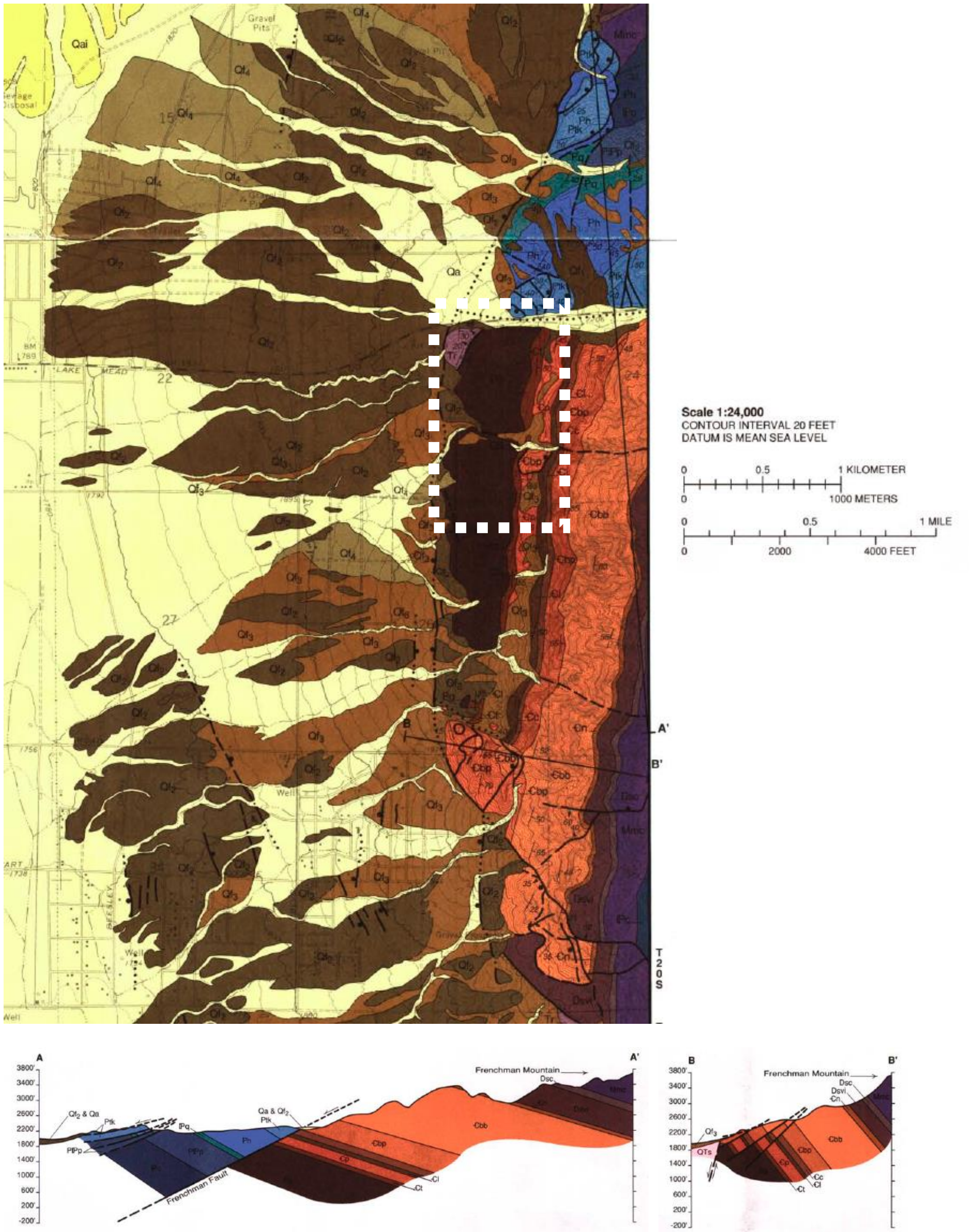


Figure 3 – Portion of geologic map and cross sections of Las Vegas NE Quadrangle from Matti et al., (1993). Summit of Frenchman Mountain lies just to the east of the mapped area in the Frenchman Mountain Quadrangle. Dashed box indicates area where samples were collected for this study.

2012). Rowland et al. (1990) and Eaton et al. (2012) also indicate that the FMB has not undergone any significant vertical axis rotation, which has affected many structural blocks surrounding the Las Vegas Valley Shear Zone (LVVSZ). The mechanism for westward translation is debated, but prevailing theories suggest movement due to the LVVSZ (Longwell 1971, 1974) or the Lake Mead Fault System (Bohannon 1979, 1984).

Although the pre-extensional geology of the region is complicated, Wernicke et al. (1988) stated that rocks in the vicinity of Lake Mead can be restored with some degree of confidence due to the vast exposure of the Cordilleran miogeocline and hence provide an ideal place to study extensional structures. This observation and the lack of vertical axis rotation coupled with an increasingly accepted translation vector (Rowland et al., 1990; Eaton, 2012) provide good constraints for paleomagnetic correction of the FMB. Since relatively small amounts of translation only marginally affect declinations (80 km of westward translation is less than one degree of longitude), paleomagnetic results in this region can be interpreted with a high degree of certainty with regard to structural and tectonic corrections.

In addition to hematite precipitation, some authors have linked sodium-metasomatism to subaerial exposure of silicate rocks. Ricordel et al. (2007), Engvik et al. (2008), and Parcerisa et al. (2010) have described albitization of basement silicate rocks that occurred in reddened rocks, often spatially related to the presence of hematite. Holness (2003) described the albitization of alkali feldspars when exposed to ion-saturated surficial fluids that penetrate to lower rocks after passing through two-feldspar silicates. The Vishnu group schists studied by Brown et al. (1979) contained between 1-2 wt% Na_2O on average, and as such could have served as a limited source of sodium for the albitization of existing oligoclase or K-feldspar. Alternatively, subsequent flooding of the exposed basement rock and circulation of evaporate-laden seawater during the Early-Middle Cambrian could have provided a source of sodium for albitization.

Subaerial exposure of the silicate basement rocks at Frenchman Mountain may have left indicators that paleomagnetic and petrographic analyses can reveal. With favorable climatic conditions, hematite precipitation within the Vishnu Group may have recorded a magnetization that could indicate the timing of exposure and the intensity of weathering processes. Additionally, the albitization of K-feldspar would suggest the penetration of Na-rich fluids into the basement. Together, hematite and albitization could provide key evidence for exposure timing and paleoclimatic conditions for southern Nevada and help to better constrain paleogeographic models.

METHODS

Samples of Proterozoic Vishnu-equivalent granite and schist and Cambrian Tapeats Sandstone were collected from the Frenchman Mountain Fault Block in Clark County, Nevada, northeast of Las Vegas. Using a gasoline-powered chainsaw modified with a Pomeroy drill, five sites of granites (6-12 samples per site) and two sites of sandstones (5-7 samples per site) were sampled from outcrop along and adjacent to Lake Mead Boulevard at different distances from the unconformity. All samples drilled in the field were oriented using a Brunton compass and clinometer prior to extraction. From the same location, three sites of granite and schist lithologies (6-23 samples per site) were collected as oriented slabs and then drilled normal to the oriented surface with a water-cooled drill press in the sample preparation lab at the University of Oklahoma.

Additional samples were collected approximately one kilometer south of Lake Mead Boulevard, along the same outcrop. At this location, three sites of granite/schist (4-12 samples per site) and four sites of sandstones (6-11 samples per site) were collected using the portable drill. Slabs were taken for an additional site of granite (17 samples) and an additional site of sandstone (13 samples) and drilled in the lab. Between the two locations, 88 samples of granite/schist and 57 samples of sandstone were collected for paleomagnetic analysis.

All samples were cut to standard 2.2 cm specimen length and then measured for natural remanent magnetization (NRM) using a 2G Enterprises three-axis cryogenic magnetometer with DC SQUIDS. Twelve representative specimens of granite were subjected to alternating field (AF) demagnetization up to 120 mT applied field to help determine magnetic mineralogy. Specimens were then subjected to thermal demagnetization in a stepwise fashion in 25°C increments for granites and schists and 20°C increments for sandstones using an ASC Model TD-48 SC thermal demagnetizer, to 675-700°C. Vishnu samples were treated in 25°C increments to reduce the total number of treatments, thereby reducing the likelihood of water dissociation and subsequent sample destruction during thermal demagnetization.

Paleomagnetic analyses were completed using the SuperIAPD program (http://www.geodynamics.no/resources.html). Data were plotted on orthogonal plots representing inclinations and declinations of the samples according to Zijderveld (1967) and then analyzed for magnetic components using principal component analysis (PCA) according to Kirschvink (1980). Components selected for further analysis and interpretation demonstrated mean angles of deviation (MAD) of less than 18°, although most samples had MAD values less than 12°. Site means were computed using Fisher (1953) statistics.

Seven specimens (three Vishnu, four Tapeats) were imparted with an isothermal remanent magnetization (IRM) at room temperature to help determine magnetic mineralogy. All specimens were first subjected to AF demagnetization at 120 mT to remove any existing remanent magnetization. Using an ASC Scientific impulse magnetizer, an IRM was then imparted in a stepwise fashion from 0 to 2500 mT and their resulting magnetizations were analyzed to determine magnetic mineralogy.

Polished thin sections were prepared of 23 sandstones and 31 granites from multiple sites and analyzed using transmitted and reflected light for occurrence and textural and spatial relationships of magnetic mineral phases. Sandstones were classified according to Folk (1965). Selected thin sections were also analyzed using an FEI Quanta 250 Scanning Electron Microscope (SEM) with Bruker energy dispersive capabilities (EDS). Backscattered electron imaging (BSE) and EDS were used to aid in identification of magnetic phases and alteration otherwise not ascertainable on an optical microscope.

RESULTS AND INTERPRETATIONS: PALEOMAGNETISM

Vishnu granites and schists

Eighty-eight samples of locally reddened granites and schists from eight sites within the Vishnu Group were collected from Frenchman Mountain, Nevada. Thermal demagnetization of specimens from four sites (FG4, VG1, VG2, and VG4) in 25°C increments removed a stable magnetic component with a northerly declination and a moderately steep up inclination after structural correction (Figs.4a, b, and c, Table 1). This component was removed from the specimens by 450°C when present, while the total magnetization of all specimens decayed by 675-680°C. Stable magnetizations with unblocking temperatures below 450°C are interpreted to reside in magnetite, while those with maximum unblocking temperatures above that are interpreted to reside in hematite. Structural corrections were made to correct Cenozoic deformation of easterly dips of ~41°.

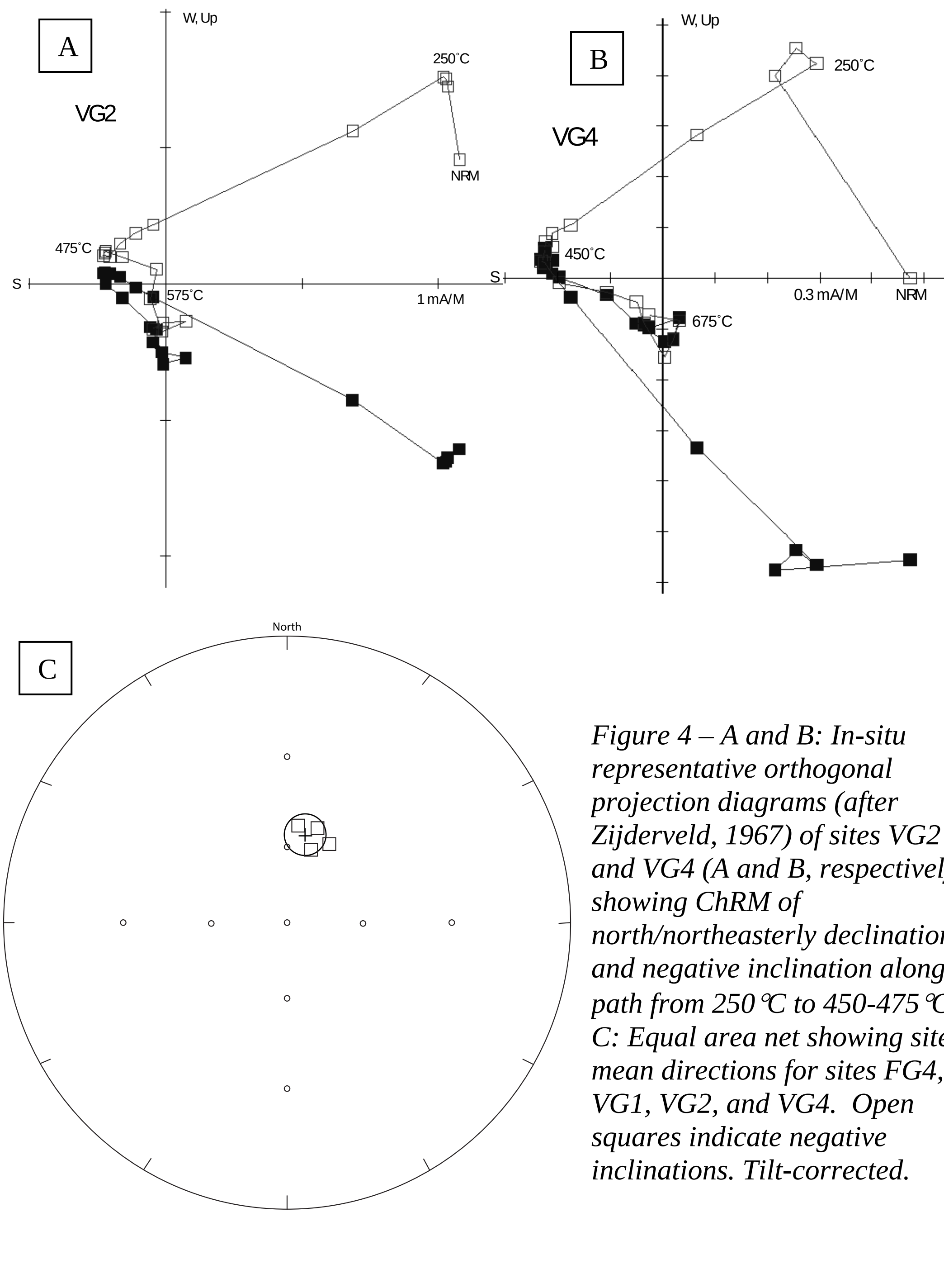
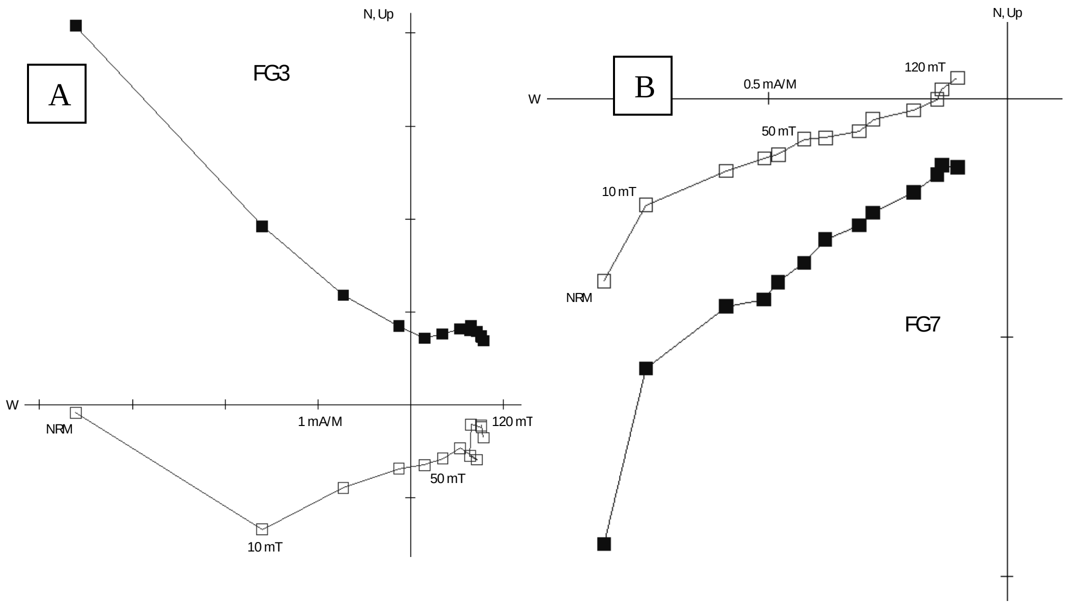


Figure 4 – A and B: In-situ representative orthogonal projection diagrams (after Zijderveld, 1967) of sites VG2 and VG4 (A and B, respectively), showing ChRM of north/northeasterly declination and negative inclination along path from 250℃ to 450-475℃. C: Equal area net showing site mean directions for sites FG4, VG1, VG2, and VG4. Open squares indicate negative inclinations. Tilt-corrected.

The stable component represented in Figure 4 is interpreted as the characteristic remanent magnetization (ChRM) of Vishnu sites that held a stable remanence. The ChRM is defined by a declination and inclination of 17.7° and -55.1°, N = 56, k = 163.5, α_{95} = 7.2°. The calculated VGP of 16.3°S latitude, 130°W longitude (d_p = 7.3°, d_m = 10.2°) plots at approximately 1440 Ma on the Mesoproterozoic portion of the apparent polar wander path (APWP) for North America (Fig. 10; Harlan et al., 2008).

Specimens from sites FG3 (N = 6) and FG7 (N = 6) were subjected to stepwise AF demagnetization from 0-120 mT. In site FG3, AF demagnetization removed a north-northwesterly and moderate down component (D = 343°, I = 46.7°, N = 5, k = 23.3, α_{95} = 16.2) after structural correction (Fig. 5). Site FG7 also yielded a stable magnetization: the site mean direction was southwesterly and moderate down (D = 230.3°, I = 45.8°, N = 6, k = 18.3, α_{95} = 16.1) (Fig. 5). Both magnetizations are interpreted to be held in magnetite based on significant loss of magnetic intensity (60-80% reduction) during AF demagnetization. VGP calculation for site FG3 gives a paleopole position of 73.4°N latitude and 130°E longitude (d_p = 13.4°, d_m = 20.9°), which falls south of the Cenozoic portion of the APWP for North America (Fig. 9). VGP calculation for site FG7 produces a paleopole position of 10.9°S latitude and 159.2°W longitude (d_p = 13.1°, d_m = 20.5°), which plots at approximately 1300 Ma on the Mesoproterozoic portion of the APWP for North America (Fig. 10; Harlan et al., 2008). Subsequent stepwise thermal demagnetization of both sites produced scattered results at higher unblocking temperatures.



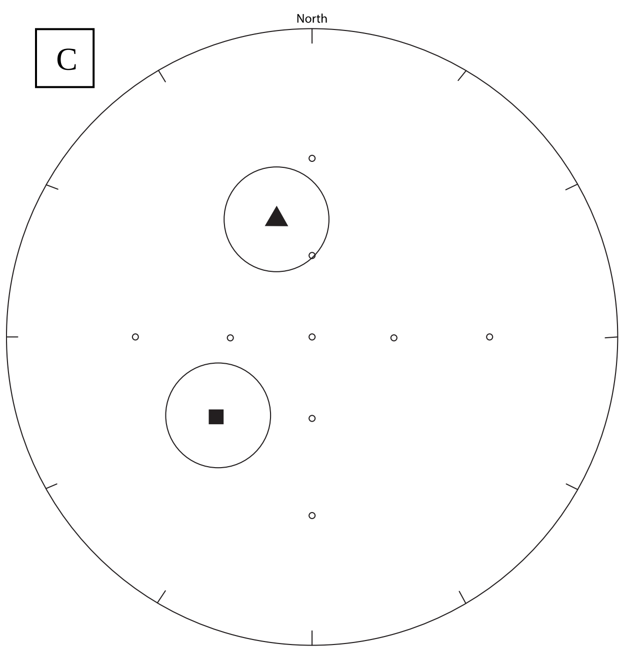


Figure 5 – A and B: In-situ orthogonal projections according to Zijderveld (1967) of AF demagnetization of sites FG3 and FG7. Stable AF decay of two separate components is exhibited, with both sites having only 10-20% of NRM strength remaining after AF demagnetization. C: Equal area net of site means with α_{95} cone of confidence circles. Triangle is FG3, square is FG7. Tilt-corrected.

Stable magnetizations were found with unblocking temperatures above 450°C in individual specimens from multiple sites at different stratigraphic levels. However, their statistical groupings were relatively poor and large α_{95} angles (20-25°) were prevalent with those components (Fig. 6). Qualitatively, these two components exhibit mostly southerly to westerly declinations and moderate inclinations, but due to low N/N_0 values are not statistically significant enough to warrant robust interpretation.

In addition to components with higher unblocking temperatures, a viscous remanent magnetization (VRM) was removed from many samples, exhibiting a northerly declination and steep positive inclination. This component was removed by thermal demagnetization with maximum unblocking temperatures usually below 300°C, excepting minor outliers that unblocked between 300-350°C. It is interpreted as the Modern field component.

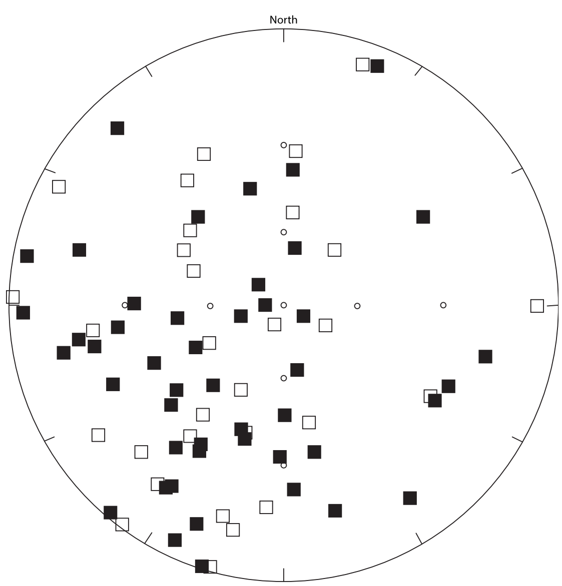


Figure 6 - Equal area net showing tilt-corrected directions of stable high temperature (>575°C maximum unblocking temperature) components in all Vishnu samples. Open squares indicate negative inclinations, closed squares denote positive inclinations.

Site	Dec (°)	Inc (°)	N/N_o	k	α_{95} (°)	VGP Lat	VGP Long	d_p (°)	d_m (°)
FG4	18.0	-59.9	18/23	149.5	2.8				
VG1	18.1	-51.6	11/12	165.9	3.6				
VG2	7.1	-52.4	10/10	140	4.1				
VG4	28.6	-55.5	17/17	8.52	13				
Mean	*17.7*	*-55.1*		*163.5*	*7.2*	*S16.3°*	*W129.9°*	*7.3*	*10.2*

Table 1 - Site statistics for thermally demagnetized Vishnu group granites and schists that yielded a stable magnetization with maximum unblocking temperatures below 450°C. Declination and inclination (°) for magnetic directions. N/N_o represents total number of specimens used to calculate site mean with respect to total number of specimens measured in that site; precision parameter, k, represents grouping; α_{95} represents 95% cone of confidence around pole; virtual geomagnetic pole (VGP) latitude and longitude were calculated from declination and inclination; d_p/d_m represent major/minor ellipse axes of the 95% cone of confidence.

Tapeats Sandstone

Fifty-seven samples of the Tapeats Sandstone were collected from the same locations as the Vishnu Group rocks from Frenchman Mountain, NV. Thermal demagnetization of specimens from site FSS3 (N = 7) in 20°C increments removed a stable magnetic component with a maximum unblocking temperature of approximately 340-360°C and declination and inclination of 49.3° and 19.2° (Fig. 7), which translated to 51.5° and -14.4° (N = 6, k = 26.6, α_{95} = 13.2°) after structural correction (bedding attitude measured at 350/41°E). Calculating a VGP for this site mean yielded a paleolatitude and longitude of 25°S and 173.9°W (d_p = 6.9°, d_m = 13.5°) which plots just to the southeast of the Middle Cambrian portion of the APWP for North America (Fig. 9). This component is interpreted to reside in magnetite based on unblocking temperature.

Additional specimens of Tapeats Sandstone yielded mixed results: some specimens did not exhibit any resolvable stable magnetic components (Fig. 7), while others showed stable decay. Those that exhibited stable decay did not produce any statistically significant site means when plotted on an equal area net (Fig. 8). Their directions were scattered, which is consistent with the paleomagnetic results reported for Tapeats Sandstone samples by Gillett (1982). High temperature components were found to be stable in some samples—these components typically had unblocking temperatures in the 600-680°C range and therefore are interpreted to reside in hematite. Their directions were randomized as well (Fig. 8), which is also consistent with the findings of Gillett (1982).

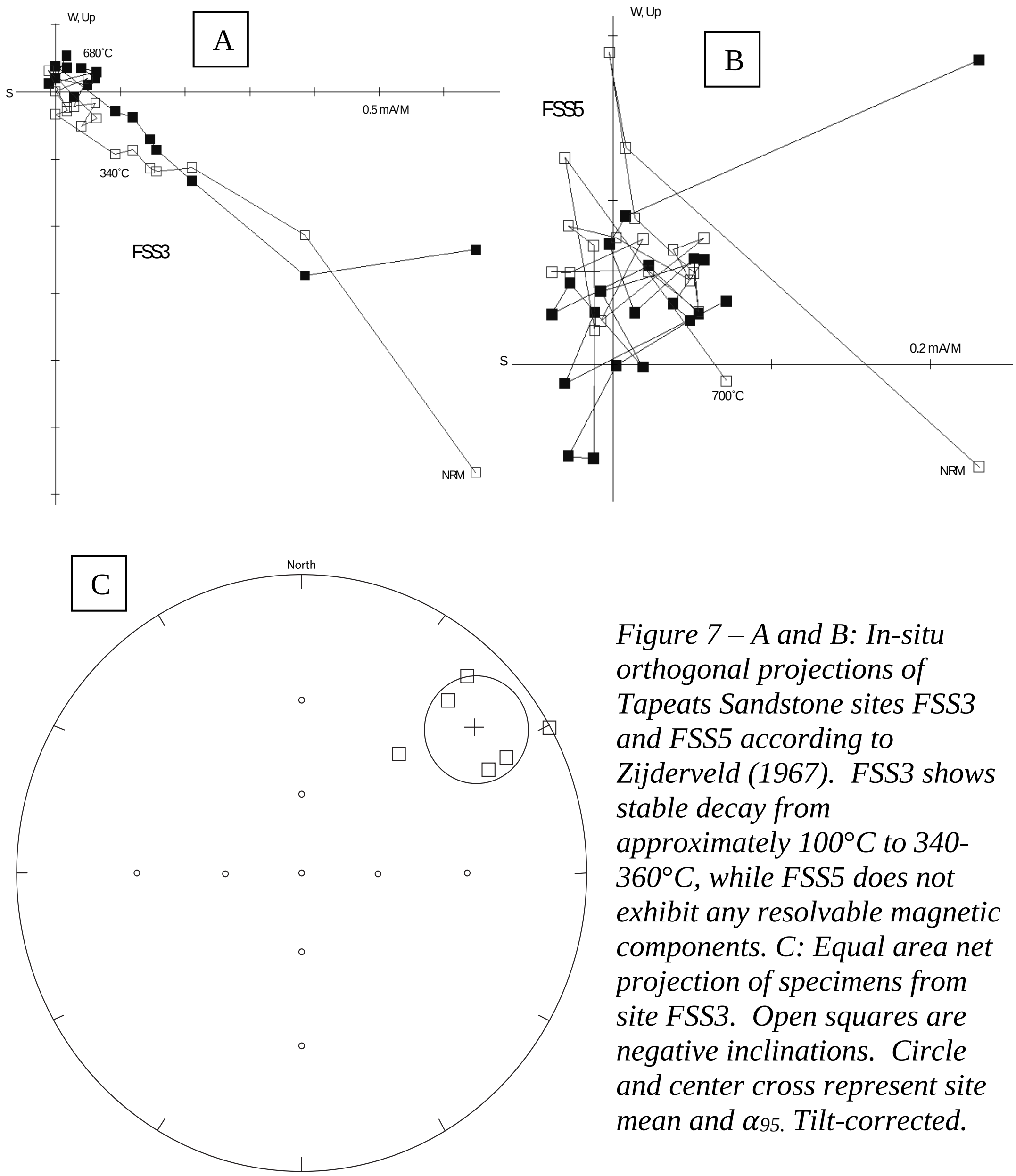


Figure 7 – A and B: In-situ orthogonal projections of Tapeats Sandstone sites FSS3 and FSS5 according to Zijderveld (1967). FSS3 shows stable decay from approximately 100°C to 340-360°C, while FSS5 does not exhibit any resolvable magnetic components. C: Equal area net projection of specimens from site FSS3. Open squares are negative inclinations. Circle and center cross represent site mean and α_{95}. Tilt-corrected.

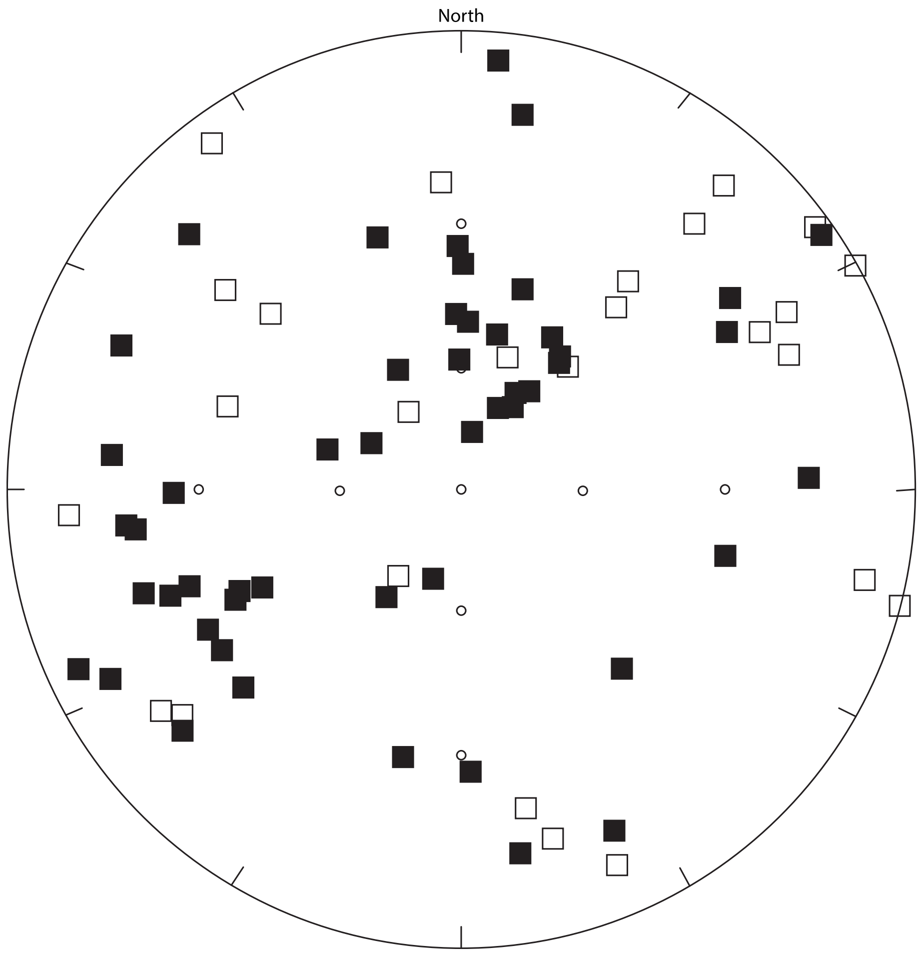


Figure 8 - Equal area net with all stable magnetic components for Tapeats Sandstone specimens. Filled squares are positive inclinations, open squares are negative inclinations. Tilt-corrected.

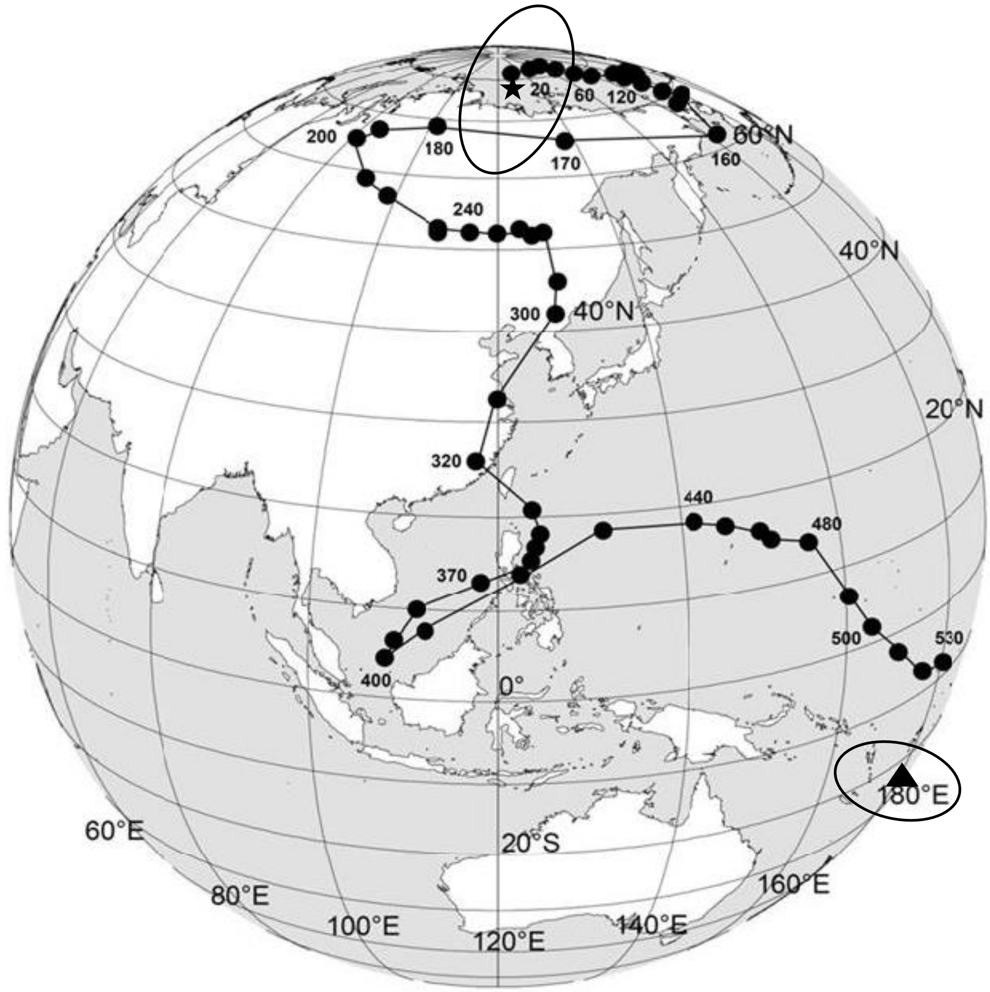


Figure 9 – Phanerozoic apparent polar wander path for North America (Torsvik et al., 2012). Star and associated confidence ellipse represent VGP for Vishnu site FG3. Triangle and associated ellipse represent Tapeats site FSS3. All other paleopoles found in this study plot to the east or southeast of the 530 Ma pole position.

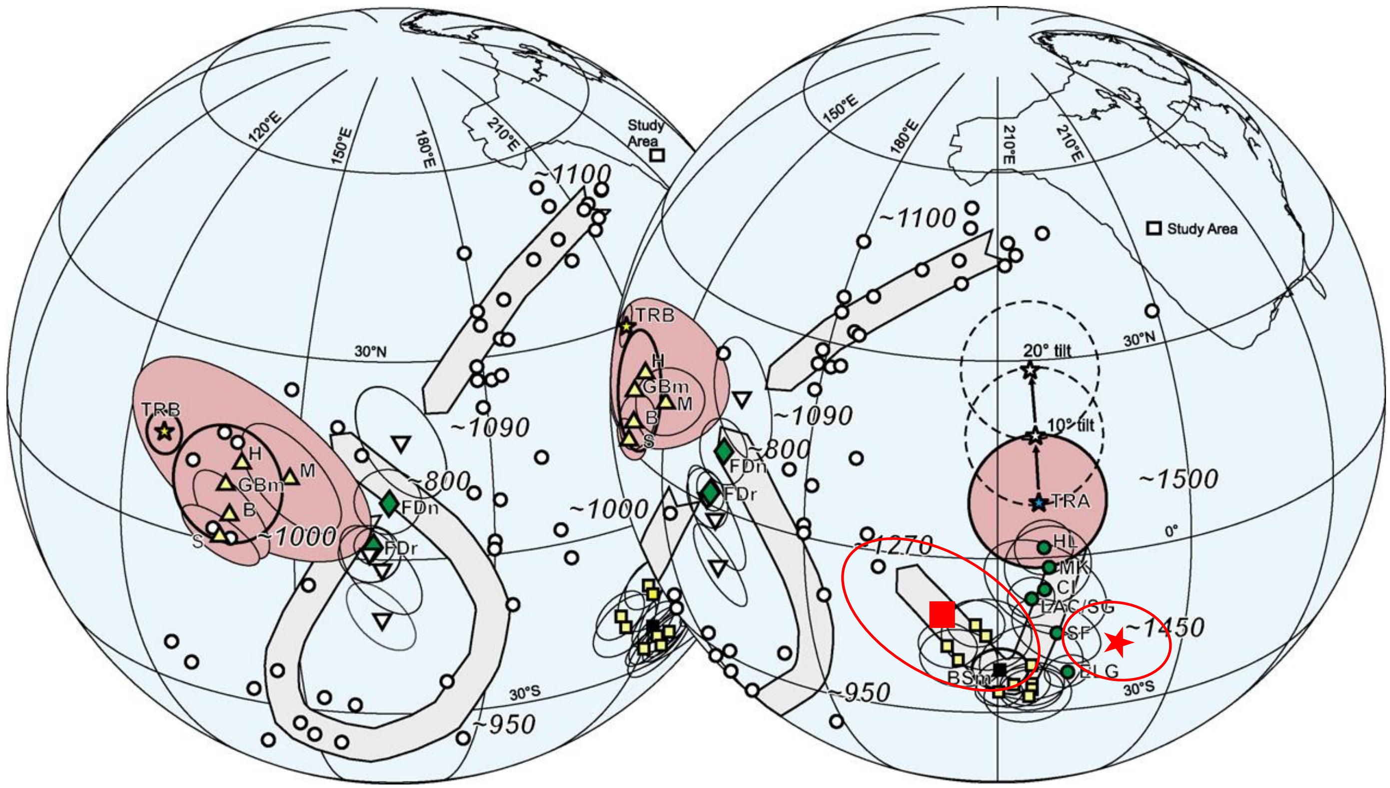
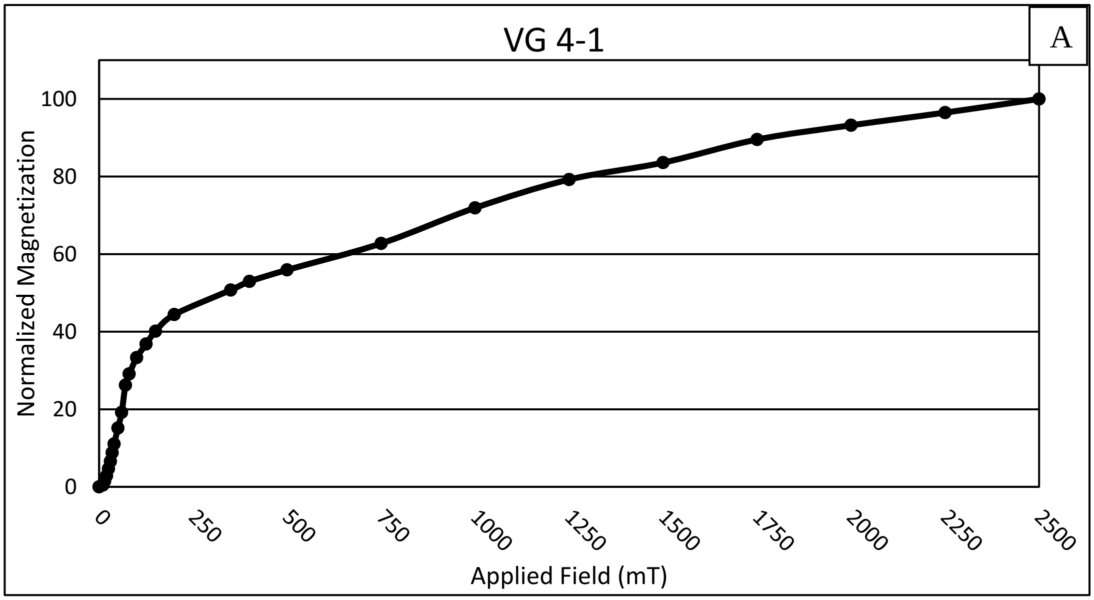


Figure 10 - Proterozoic apparent polar wander path for North America (modified from Harlan et al., 2008). Red star and associated confidence ellipse represent ChRM found in Vishnu Group specimens. Square and associated confidence ellipse represent stable component found in AF demagnetization of site FG7.

RESULTS AND INTERPRETATIONS: ROCK MAGNETISM

Three specimens of Vishnu granite and four specimens of Tapeats Sandstone were imparted with an IRM under applied fields up to 2.5 Tesla. Subsequent analysis reveals the presence of multiple magnetic minerals in each lithology. Granite specimens (Figs. 11a and b) contain both a low coercivity and high coercivity component, since acquisition begins at low applied fields (< 100 mT) but continues to increase in intensity at higher applied fields (> 1000 mT). This is consistent with petrographic results that reveal both titanomagnetite and hematite (Fig. 13) in the granite. Tapeats specimens exhibit variable behavior—two specimens steadily acquire magnetization beginning at low applied fields and steadily continue to acquire magnetization at higher applied fields (Fig. 12a), while two specimens acquire magnetization at slightly elevated applied fields (60 – 1000 mT) before they appear to approach saturation (Fig. 12b). These results support the interpretation of the presence of multiple magnetic minerals indicated by paleomagnetic analysis and petrographic study.



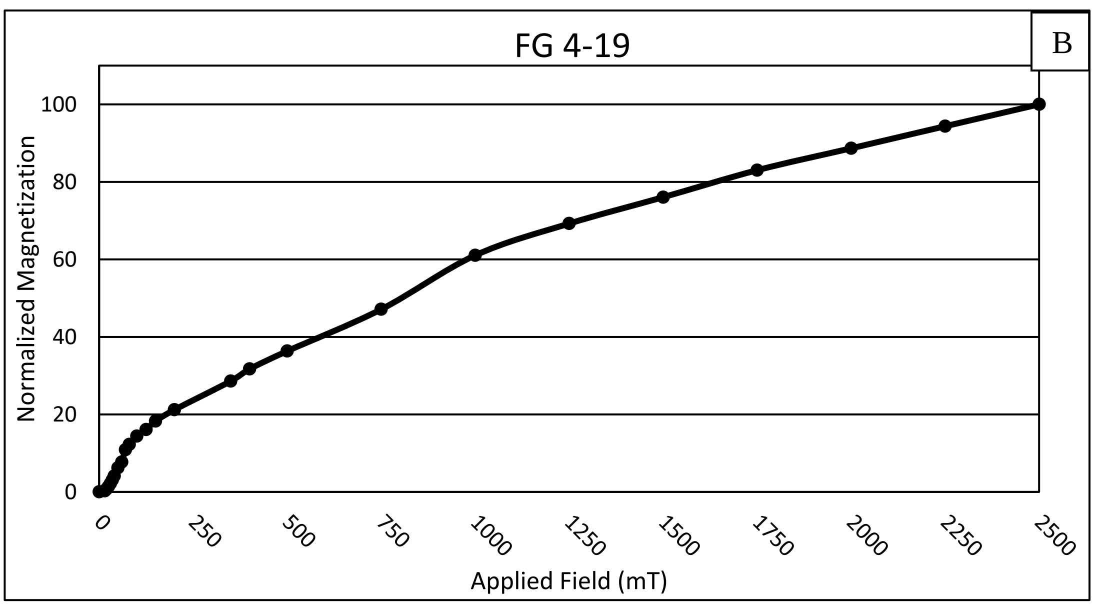


Figure 11 - IRM acquisition curves of Vishnu granite specimens VG 4-1 (A) and FG 4-19 (B). Both low and high coercivity minerals are present, indicated by acquisition at both low and high applied fields, though VG 4-1 demonstrates a higher proportion of lower coercivity minerals than FG 4-19.

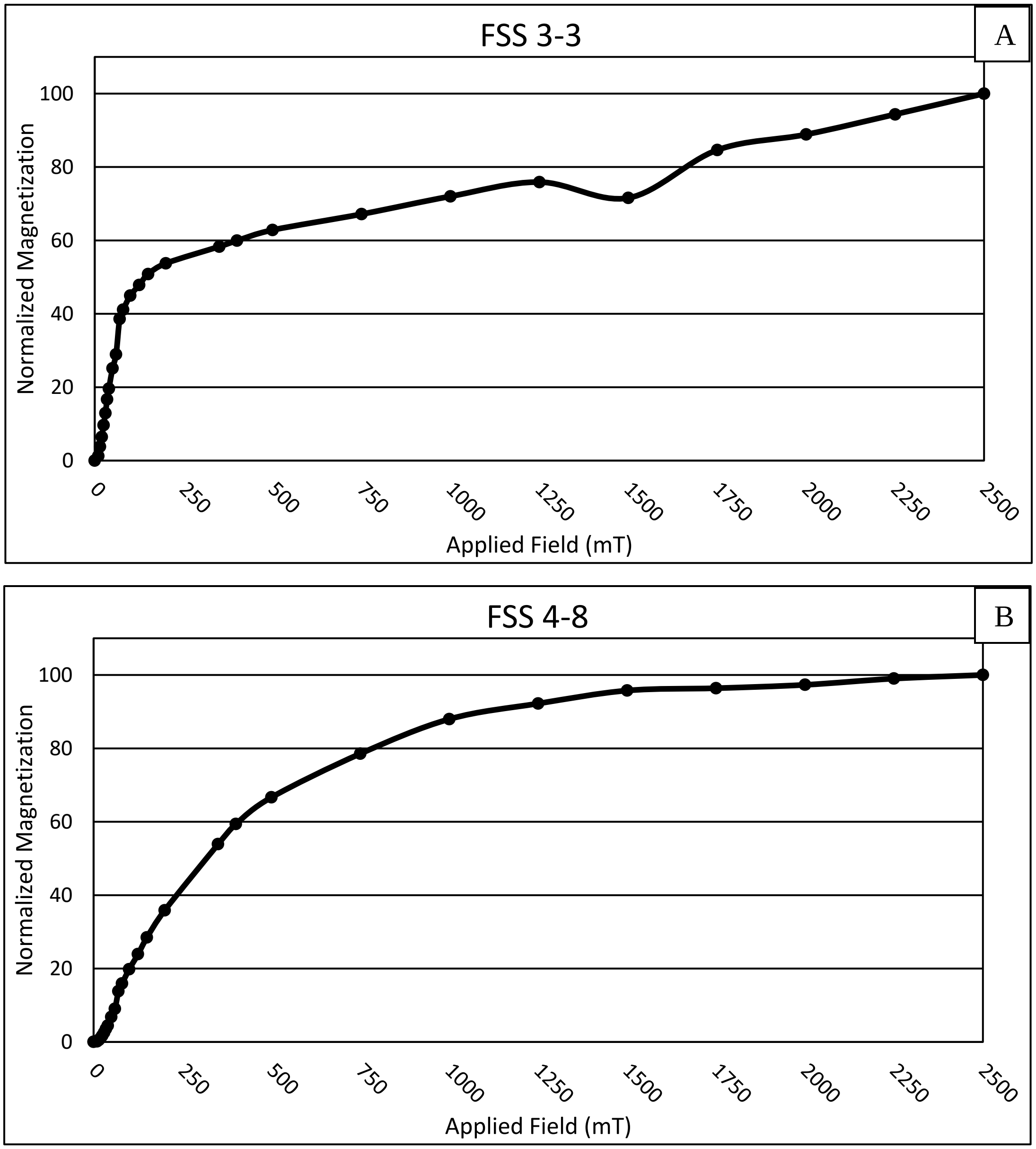


Figure 12 - IRM acquisition curves of Tapeats Sandstone. FSS 3-3 (A) shows rapid acquisition of magnetization over low applied fields followed by continuous acquisition at higher fields, while FSS 4-8 (B) shows acquisition during moderate applied fields followed by slower acquisition at higher fields.

RESULTS AND INTERPRETATIONS: PETROGRAPHY

Vishnu rocks from Frenchman Mountain are typical biotite-garnet schists with large restite granite inclusions. Abundant hematite, both specular and pigment, are found in granite and schist samples. Reflected light microscopy clearly shows red internal reflections adjacent to highly reflective fracture-fill specular hematite (Fig. 13a) and replacement hematite (Fig. 13b). Specular hematite also appears to replace other mineral grains in many samples, such as in Figure 13b. EDS analysis on the SEM confirms the presence of iron and lack of other cations within the hematite (Fig. 13c), while showing that the surrounding mineralogy is likely potassium feldspar or another iron-poor mineral, such as muscovite. In some samples, specular hematite appears to precipitate in place of dissolved grains of alkali feldspar (Fig. 13d). This is particularly apparent in samples from sites FG3, FG5, FG8, and all usable VG samples, which are likely restite portions within the metamorphosed unit and are more suitably classified as granites instead of schists. In samples from FG2 and FG7, hematite appears to replace biotite more often than any other mineral. This is likely due to the heavy modal portion of biotite in garnet-biotite schists that compose the majority of the Vishnu Group in the area.

Albitization of alkali feldspars is visible in both optical and SEM microscopy. Primary plagioclase is extremely rare in the host Vishnu rock, and is almost completely altered to sericite where present. In sample FG 3-3 (Fig. 14), albitization of the host alkali feldspar originated in a fracture that was subsequently

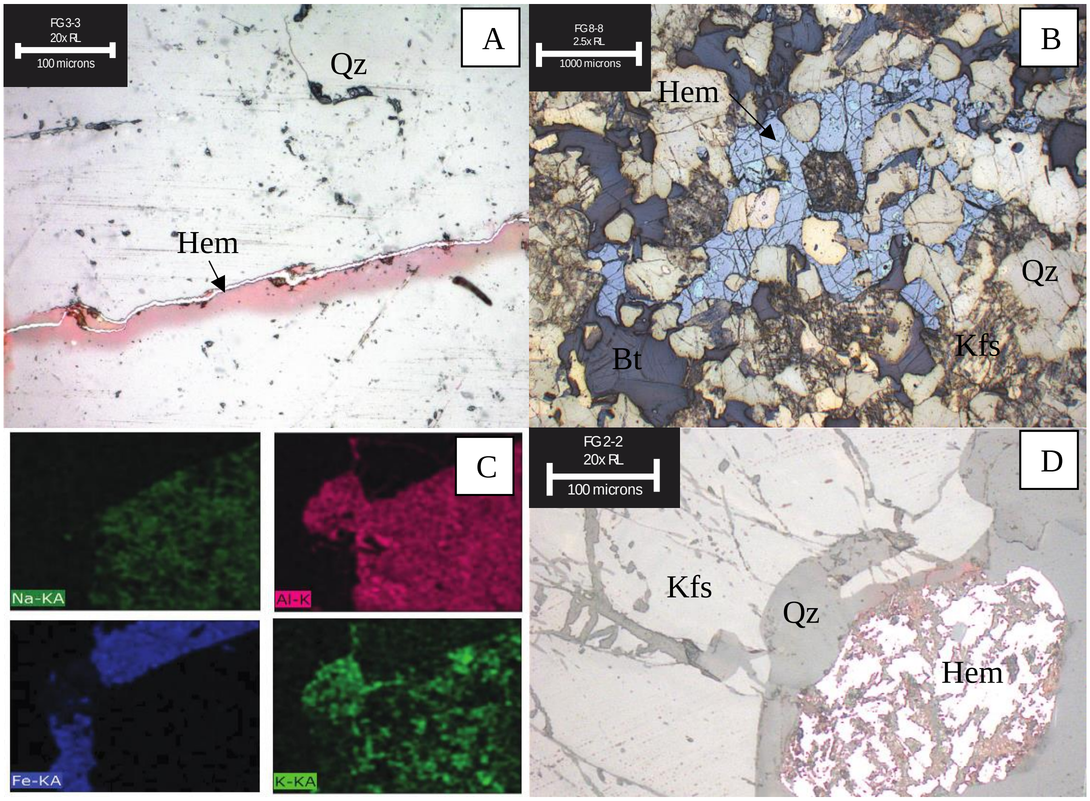


Figure 13 - a) Red internal reflection adjacent to highly reflective hematite in FG3-3. b) Hematite replacing biotite in FG8-8. c) EDS of FG3-3 showing hematite surrounding edge of larger feldspar grain, with muscovite in center of hematite. Clockwise, from top left: Na, Al, Fe, K. d) Highly reflective hematite with red internal reflections in FG2-2.

filled by specular hematite. EDS mapping indicates little to no potassium or calcium within albitized feldspar. (Fig. 14).

Optical microscopy of Tapeats Sandstone samples reveals abundant quartz overgrowth and sutured quartz grains. The Paleozoic section at the Nevada Test Site, only a few kilometers to the north, is over 12,000 meters thick (Ekren, 1968)—diagenesis of the sandstones at that depth would be capable of creating quartz overgrowths and sutures. The sandstones are typically well sorted, sub-rounded quartzarenites, with few feldspars or other detrital grains visible using optical methods. Of interest to this study are localized regions of hematite that appear to be spatially related to dissolved or replaced alkali feldspar grains (Fig. 15). This is confirmed using SEM microscopy, as the affected grains are typically very small (100-400 microns).

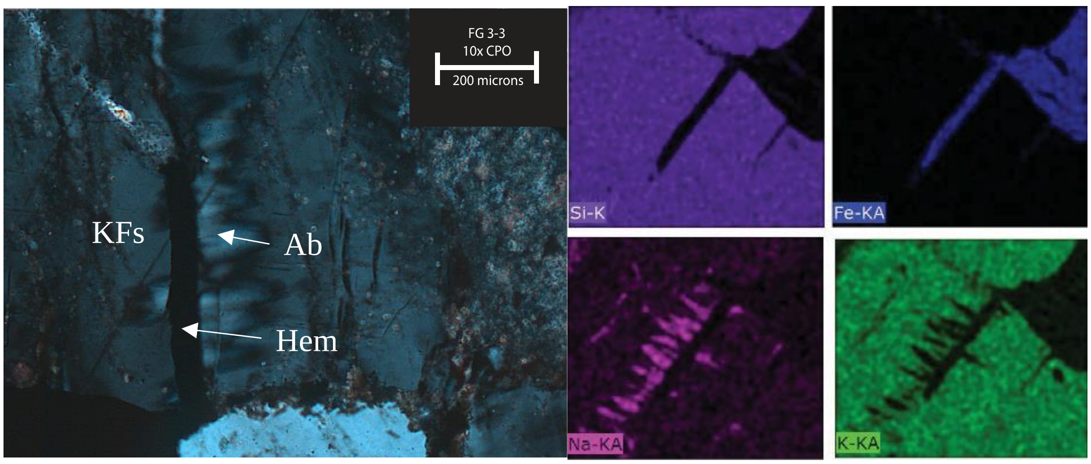


Figure 14 - Albitization of alkali feldspar in FG3-3. Image on left is under crossed nicols at 10x magnification. On right, EDS maps of Si, Fe, Na, and K showing zoning of Na and K (lower left and lower right, respectively) emanating from fracture filled by hematite (Fe on upper right).

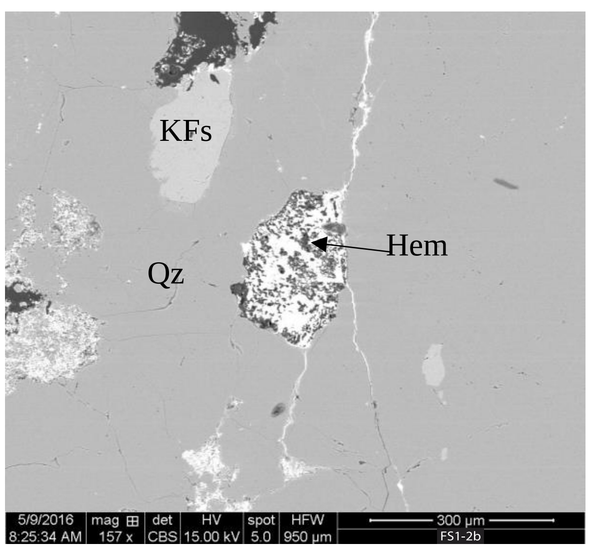


Figure 15 – SEM backscattered image of alkali feldspar grain in Tapeats sample FS1-2b replaced by hematite. Adjacent fracture is filled with hematite. Dominant grey is quartz.

DISCUSSION

Vishnu Group

The Vishnu group schists and granites were emplaced 1.75-1.74 Ga and reached peak metamorphic conditions soon after, approximately 1.70-1.69 Ga during the Yavapai orogeny [Karlstrom et al., 2012 (1)]. Magnetite grains within the Vishnu likely held the magnetic remanence acquired during metamorphism to lower amphibolite facies (~550°C) which crystallized the garnet and biotite grains. The time gap between the Grand Canyon Supergroup (terminating with an angular unconformity between the Sixtymile Formation and the Tapeats Sandstone) is estimated at around 175 Ma [Karlstrom et al., 2012 (2)], which indicates this as a minimum amount of time for exposure of the Vishnu Group at Frenchman Mountain prior to deposition of the Tapeats Sandstone in the mid-Cambrian.

All Vishnu Group samples were collected from outcrops spanning less than two kilometers in length. Latent heat retained during the Yavapai orogeny and subsequent extended cooling time does present the possibility of multiple geomagnetic fields being recorded in rocks that acquired magnetizations during that timeframe. Another issue, despite advances in Proterozoic APW constraint by Spall (1971), Larson et al. (1973), McCausland et al. (2007), and Harlan et al. (2008) is the poorly understood Proterozoic APWP. The possibility of multiple magnetic field configurations coupled with the lack of a robust Precambrian APWP for North America during the latest Proterozoic (e.g. Mitchell et al., 2011) prevents reliable paleopole plotting for any magnetic components that exhibit directions consistent with that timeframe.

The interpreted ChRM from Vishnu sites FG4, VG1, VG2, and VG4 yielded a paleopole at 16.3°S, 130°W longitude, which plots near 1440 Ma on the Mesoproterozoic portion of the APWP (Harlan et al., 2008), and is comparable to the primary pole position found in the St. Francois Mountains region of Missouri and described by Meert et al. (2002). This pole falls within the 95% confidence ellipse of that primary pole position. This suggests that the magnetization found in these sites may have been acquired during later stages of metamorphism, as the rocks cooled below the Curie temperature. Karlstrom et al. (1997) and Timmons et al. (2001) estimate the cooling of the Vishnu Group in the Grand Canyon to below 200°C at approximately 1200-1300 Ma, suggesting the temperatures may have still been high enough to preserve a metamorphism-induced thermoremanent magnetization (TRM) at 1440 Ma. Possible alternate mechanisms for this magnetization as a remagnetization are elusive; little is known about deposition of sedimentary rocks in southern Nevada prior to deposition of the Tapeats Sandstone during the Cambrian. The Neoproterozoic sedimentary rocks found in the Grand Canyon are not found in southern Nevada—the Tapeats Sandstone rests directly on the basement where outcrop is visible. Surface exposure during the pre-Tapeats time period could have provided opportunity for weathering fluids to permeate the basement rock and precipitate hematite, but the remagnetization of magnetite would have required an alternate mechanism. The inconsistent occurrence of this magnetization in rocks studied in this work could be the result of local paleotopographic relief during the time of exposure.

The probable exposure of the basement during the late Proterozoic coupled with increased atmospheric CO_2 levels (Bao et al., 2008) would have likely led to increased chemical weathering rates and the precipitation of specular hematite (e.g. Ricordel et al., 2007; Franke et al., 2010; Dulin, 2014; and others). Hematite precipitated during exposure would have acquired a magnetization consistent with that timeframe, but the majority of the magnetic remanence found in this study was removed at unblocking temperatures more consistent with magnetite. In addition, the calculated VGP longitude for the pole is too far east to be confidently classified as Neoproterozoic. The remanence is therefore interpreted as a TRM acquired during the latest stages of metamorphism in the Mesoproterozoic, based on magnetite acting as the dominant magnetic carrier and the unknown nature of the paleogeography and stratigraphy during the time following metamorphism. Magnetic components with similar directions that unblocked above 575°C were not pervasive enough to indicate widespread precipitation of hematite during the time of magnetite magnetization, but did occur in some specimens. This suggests that local climatic conditions in the region during the Mesoproterozoic could have been conducive to hematite precipitation (e.g. Walker et al., 1981; Dulin, 2014), but conditions in the Neoproterozoic were likely not as favorable for increased rates of physical and/or chemical weathering.

Several local factors can and do exert influence over the rate of chemical weathering, including temperature (Millot et al., 2003; West et al., 2005; Anderson, 2007; Montañez et al., 2007; Gislason et al., 2009), altitude (Riebe et al. 2004), and precipitation (Dupre et al., 2003; Gutierrez, 2005; Gislason et al., 2009; Shin et al., 2011; and others). Wallmann (2001) demonstrated a strong link between atmospheric CO_2 levels and chemical denudation rates during the Cenozoic. Volcanic eruptions such as the Deccan Traps in the Late Cretaceous are capable of changing atmospheric CO_2 levels enough to drastically alter chemical weathering rates as a response to CO_2 variations (Dupre et al. 2003). Hamilton et al. (2014) found alteration in the Long Mountain Granite in southern Oklahoma that was attributed to local tectonic and/or weathering events.

Albitization of feldspars has also been suggested to be an indicator of increased chemical weathering processes (Parcerisa et al. 2010). Although some albitization of alkali feldspars is noted in the Vishnu Group rocks of this study, the phenomenon is not pervasive enough to suggest a significant increase in chemical weathering rates. This could be a result of the lack of plagioclase in the sedimentary rocks that were metamorphosed to form the Vishnu, as the more granitoid portions of the rock contain little to no albite, which in turn leads to the issue of a lack of an adequate sodium source for albitization. Still, Lee and Parsons (1997) state that the albitization of alkali feldspars in granites at depth are possibly fluid-driven, which supports the albitization seen in this study adjacent to a hematite-filled fracture. It is possible that albitization occurred in the Vishnu group using externally-sourced sodium, perhaps carried in supergene fluids that permeated the uppermost basement along with oxidized iron cations. To this end, van de Kamp (2016) suggests the release of potassium during illitization of clays could provide vacant sites for seawater-derived sodium that would otherwise precipitate evaporites.

The mechanism of hematite precipitation in crystalline basement rocks by supergene fluids does hold (Parnell et al., 2000; Ricordel et al., 2007). Although this study did reveal magnetizations held in hematite, the inconsistent nature of directions, poor understanding of the Neoproterozoic APWP, and an incomplete/unknown Proterozoic stratigraphic history of the study area prevent this work from providing meaningful support for the mechanism during the proposed exposure window. Further work to constrain the APWP during the time from ~800Ma to ~530Ma will help determine if the poles found in this study are supportive of the mechanism.

<u>Tapeats Sandstone</u>

Ancient magnetizations in specimens of the Tapeats Sandstone exhibit a highly scattered distribution, which is consistent with the findings of Gillett (1982). Although individual specimens do contain stable magnetic components at multiple temperature ranges, the magnetic directions group poorly and most sites show little to no correlation between directions. Site FSS3 was the only Tapeats site with a statistically significant site mean—that direction led to a paleopole of 25°S latitude and 173.9°W longitude, which indicates a possible late Proterozoic to early

Cambrian magnetization. This is consistent with the time of deposition of the Tapeats Sandstone, and therefore the magnetization is possibly a locally preserved primary magnetization or a remagnetization acquired very soon after deposition. The magnetization is therefore interpreted to be a detrital remanent magnetization (DRM) held in detrital magnetite grains.

The presence of stable high-temperature magnetic components but lack of consistent magnetic directions is similar to results found previously by Gillett (1982) in the same Tapeats Sandstone and Dulin (2014) in rocks at Byers Canyon and Unaweep Canyon, Colorado. This randomized pattern could be caused by the size of the original magnetic mineral assemblage or varying levels of oxidation and other diagenetic processes over long periods of time, therefore acquiring magnetizations from many field directions, as originally set forth by Gillett (1982).

CONCLUSIONS

The results of this study are somewhat inconclusive when considering the initial question of whether increased chemical weathering occurred during the latest Proterozoic to early Cambrian in Nevada. While paleomagnetic evidence given here indicate that chemical weathering was not as prevalent as expected, other lines of evidence suggest that some degree of iron oxidation did occur and could be indicative of increased chemical weathering during the Neoproterozoic or earlier. The presence of specular fracture-fill hematite could be indicative of higher atmospheric CO_2 levels and local climatic patterns that led to variable oxygenation and weathering rates. However, sampling of rock at different distance from the unconformity did not correlate with magnetic intensities, as in previous studies (e.g. Hamilton et al., 2014). Local altitude, precipitation amounts/intensities, and temperatures could have played a role in determining the intensity of weathering. Additionally, atmospheric CO_2 levels could have shifted and caused fluctuations in the weathering rates and precipitation/alteration of those minerals. Albitization of K-feldspar, to some extent, may also indicate the weathering of the basement due to weathering fluid penetration. However, the presence of evaporitic minerals could be a sign of K-metasomatism due to evaporite formation and subsequent illitization of detrital clays during deposition of the Tapeats Sandstone.

Further work on the APWP for late Proterozoic to earliest Phanerozoic time needs to be completed to ascertain the implications of the paleopoles found in magnetic remanence in the Vishnu Group rocks. Only then can we better understand the effects that atmospheric CO_2 had on the weathering of silicate rocks in this region, as well as the converse effect of the weathering of the rocks on CO_2 levels.

REFERENCES

Anderson, R. E., 1998, Structural relations between Las Vegas basin and the Frenchman Mountain/Sunrise Mountain block, southern Nevada. NBMG Open-File Report 24.

Anderson, S.P., 2007, Biogeochemistry of glacial landscape systems: Annual Review of Earth and Planetary Sciences, vol. 35, pp. 375-399.

Bao, H., Lyons, J. R., & Zhou, C., 2008, Triple oxygen isotope evidence for elevated CO2 levels after Neoproterozoic glaciation: Nature (London), 453 (7194), 504-506.

Bohannon, R.G., 1979, Strike-slip faults of the Lake Mead region of southern Nevada: Cenozoic paleogeography of the western United States: Pacific Coast Paleogeography Symposium, p. 129-139.

Bohannon, R.G., 1984, Nonmarine sedimentary rocks of Tertiary age in the Lake Mead region, southeastern Nevada and northwestern Arizona: U. S. Geological Survey, Reston, VA, United States (USA), Report P-1259, 72.

Brown, E.H., Babcock, R.S., Clark, M.D., & Livingston, D.E., 1979, Geology of the older Precambrian rocks of the Grand Canyon Part I. Petrology and structure of the Vishnu Complex: Precambrian Research, 8(3), 219-241.

Burgert, B. L., 1972, Petrology of the Cambrian Tapeats sandstone, Grand Canyon, Arizona.

Chadwick, A., Kennedy, E., & Soria, J., 1998, In Canaveras J. C., Garcia del Cura M. A., Soria J., Melendez Hevia A. and Soria A. R. (Eds.), Evidence for deep water deposition of the Tapeats sandstone, Grand Canyon, Arizona, USA Univ. Alicante, Alicante.

Clark, M.D., 1979, Geology of the older Precambrian rocks of the Grand Canyon: Part III. Petrology of mafic schists and amphibolites: Precambrian Research,8(3), 277-302.

Creer, K. M., 1968, Arrangement of the Continents during the Paleozoic Era: Nature, v. 219, no. 5149, p. 41-44.

Dulin, S.A., 2014, Paleomagnetism as a Tool for Determining Diagenetic, Depositional, and Erosional Events as Recorded in Sedimentary and Igneous Rocks, ProQuest Dissertations and Theses.

Dupre, B., Dessert, C., Oliva, P., Godderis, Y., Viers, J., Francois, L., Millot, R. & Gaillardet, J. 2003, Rivers, chemical weathering, and Earth's climate: Comptes Rendus – Academie des Sciences. Geoscience, vol. 335, no. 16, pp. 1141-1160.

Eaton, L., Hanson, A., Meacham, S., Smith, G., & Taylor, W., 2012, Determining the Significance and Sense of Offset of the Frenchman Mountain Fault Las Vegas, Nevada: A Paired Basin Analysis and Structural Analysis, ProQuest Dissertations and Theses.

Ekren, E. B., 1968, Geologic setting of Nevada test site and Nellis air force range: Memoir - Geological Society of America, 11-19.

Engvik, A. K., Putnis, A., Fitzgerald, J. D., and Austrheim, H., 2008, Albitization of granitic rocks: the mechanism of replacement of oligoclase by albite: The Canadian Mineralogist, v. 46, p. 1401-1415.

Fisher, R., 1953, Dispersion on a Sphere: Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, v. 217, no. 1130, p. 295-305.

Folk, R., 1961, Petrology of sedimentary rocks: Austin, Tex.: Hemphill's.

Franke, C., Thiry, M., Gomez-Gras, D., Jelenska, M., Kadzialko-Hofmokl, M., Lagroix, F., Parcerisa, D., Spassov, S., Szuszkiewicz, A., and Turniak, K., 2010, Paleomagnetic age constraints and magneto-mineralogic implications for the Triassic paleosurface in Europe: Geophysical Research Abstracts, v. 12, no. EGU General Assembly.

Gillett, S. L., 1982, Remagnetized cratonic Cambrian strata from southern Nevada: Journal of Geophysical Research, 87, 7097-7112.

Gislason, S.R., Oelkers, E.H., Eiriksdottir, E.S., Kardjilov, M.I., Gisladottir, G., Sigfusson, B., Snorrason, A., Elefsen, S., Hardardottir, J., Torssander, P. & Oskarsson, N., 2009, Direct evidence of the feedback between climate and weathering: Earth and Planetary Science Letters, vol. 277, no. 1-2, pp. 213-222.

Gutierrez, M., 2005, Developments in Earth Surface Processes, in Jr., J. F. S., ed., Climatic Geomorphology, Elsevier, p. 760.

Hamilton, M., Elmore, R.D., Weaver, B., and S.A. Dulin, 2014, Petrology and paleomagnetism of the Long Mountain Granite, Wichita Mountains, Oklahoma in Igneous and Tectonic History of the Southern Oklahoma Aulacogen; Oklahoma Geologic Survey vol. 38, p. 319-325.

Harlan, S. S., Geissman, J. W., & Snee, L. W., 2008, Paleomagnetism of Proterozoic mafic dikes from the Tobacco Root Mountains, southwest Montana. Precambrian Research, 163(3-4), 239-264.

Harland, W. B., 2007, Origins and assessment of snowball Earth hypotheses. Geological Magazine, 144(4), 633-642.

Holness, M., 2003, Growth and albitization of K-feldspar in crystalline rocks in the shallow crust: A tracer for fluid circulation during exhumation?, Geofluids, 3(2), 89-102.

Karlstrom, K.E., Heizler, M.T., Williams, M.L., 1997, $^{40}Ar/^{39}Ar$ muscovite thermochronology within the Upper Granite Gorge of the Grand Canyon, EOS Transactions of the American Geophysical Union, 78 (46), p. F784.

Karlstrom, K.E., Ilg, B.R., Hawkins, D., Williams, M.L., Dumond, G., Mahan, K., and Bowring, S.A., 2012, Vishnu basement rocks of the Upper Granite Gorge: Continent formation 1.84 to 1.66 billion years ago, in Timmons, J.M., and Karlstrom, K.E., eds., Grand Canyon Geology: Two Billion Years of Earth's History: Geological Society of America Special Paper 489, p. 7–24.

Karlstrom, K.E., and Timmons, J.M., 2012, Many unconformities make one 'Great Unconformity,' in Timmons, J.M., and Karlstrom, K.E., eds., Grand Canyon Geology: Two Billion Years of Earth's History: Geological Society of America Special Paper 489, p. 73–79.

Kennedy, E. G., Kablanow, R., & Chadwick, A. V., 1996, A reassessment of the shallow water depositional model for the Tapeats sandstone, Grand Canyon, Arizona; evidence for deep water deposition. Abstracts with Programs - Geological Society of America, 28(7), 407.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: Geophysical Journal of the Royal Astronomical Society, v. 62, no. 3, p. 699-718.

Larson, E. E., Reynolds, R., and Hoblitt, R., 1973, New Virtual and Paleomagnetic Pole Positions from Isotopically Dated Precambrian Rocks in Wyoming, Montana, and Arizona; their Significance in Establishing a North American

Apparent Polar Wandering Path: Geological Society of America Bulletin, vol. 84, no. 10, pp. 3231-3248.

Lee, M. R., & Parsons, I, 1997, Dislocation formation and albitization in alkali feldspars from the Shap granite: American Mineralogist, 82(5-6), 557-570.

Longwell, C.R., 1971, Measure of lateral movement on Las Vegas shear zone, Nevada: Geological Society of America Abstracts with Programs, v. 3, p. 152.

Longwell, C., 1974, Measure and Date of Movement on Las Vegas Valley Shear Zone, Clark County, Nevada: Geological Society of America Bulletin, 85(6), 985-989.

Matti, J. C., Castor, S. B., Bell, J. W., & Rowland, S. M., 1993, Las Vegas NE quadrangle; geologic map: Nevada Bureau of Mines and Geology, Reno, NV.

McCausland, P. J. A., Van, d. V., & Hall, C. M., 2007, Circum-Iapetus paleogeography of the Precambrian-Cambrian transition with a new paleomagnetic constraint from Laurentia. Precambrian Research, 156(3-4), 125-152.

Meert, J. G., & Stuckey, W., 2002, Revisiting the paleomagnetism of the 1.476 Ga St. Francois Mountains igneous province, Missouri: *Tectonics, 21*(2), 19.

Millot, R., Gaillardet, J., Dupre, B. & Allegre, C.J., 2003, Northern latitude chemical weathering rates; clues from the Mackenzie River basin, Canada: Geochimica et Cosmochimica Acta, vol. 67, no. 7, pp. 1305-1329.

Mitchell, R. N., Kilian, T. M., Raub, T. D., Evans, D. A. D., Bleeker, W., & Maloof, A., 2011, Sutton hotspot; resolving Ediacaran-Cambrian tectonics and true polar wander for Laurentia: Abstracts with Programs - Geological Society of America, 43(5), 319.

Montanez, I.P., Tabor, N.J., Niemeier, D., DiMichele, W.A., Frank, T.D., Fielding, C.R., Isbell, J.L., Birgenheier, L.P., and Rygel, M.C., 2007, CO2-forced climate instability and linkages to tropical vegetation during late Paleozoic deglaciation: Science, v. 315, p. 87– 91.

Parcerisa, D., Thiry, M., and Schmitt, J. M., 2010, Albitization related to the Triassic unconformity in igneous rocks of the Morvan Massif (France): International Journal of Earth Science (Geologische Rundschau), v. 99, no. 3, p. 18.

Parnell, J., Baron, M., Davidson, M., Elmore, R. D., and Engel, M., 2000, Dolomitic breccia veins as evidence for extension and fluid flow in the Dalradian of Argyll: Geologic Magazine, v. 137, no. 4, p. 447-462.

Ricordel, C., Parcerisa, D., Thiry, M., Moreau, M. G., and Gomes-Gras, D., 2007, Triassic magnetic overprints related to albitization in granites from the Morvan massif (France): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 251, p. 268-282.

Riebe, C.S., Kirchner, J.W. & Finkel, R.C., 2004 (1), Erosional and climatic effects on long-term chemical weathering rates in granitic landscapes spanning diverse climate regimes: Earth and Planetary Science Letters, vol. 224, no. 3-4, pp. 547-562.

Riebe, C.S., Kirchner, J.W. & Finkel, R.C., 2004 (2), Sharp decrease in long-term chemical weathering rates along an altitudinal transect: Earth and Planetary Science Letters, vol. 218, no. 3-4, pp. 421-434.

Rowland, S. M., 1987, Paleozoic stratigraphy of Frenchman Mountain, Clark County, Nevada, in Hill, M., ed., Cordilleran Section of the Geological Society of America: Boulder, Colorado, Geological Society of America Centennial Field Guide, v. 1, p. 53-56.

Rowland, S. M., Parolini, J. R., Eschner, E., McAllister, A. J., and Rice, J. A., 1990, Sedimentologic and stratigraphic constraints on the Neogene translation and rotation of the Frenchman Mountain structural block, Clark County, Nevada, in Wernicke, B. P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Boulder, Colorado, Geological Society of America Memoir 176.

Sears, J. W., 1973, Structural geology of the Precambrian Grand Canyon series, Arizona.

Shin, W., Ryu, J., Park, Y. & Lee, K., 2011, Chemical weathering and associated CO2 consumption in six major river basins, South Korea: Geomorphology, vol. 129, no. 3-4, pp. 334-341.

Spall, H., 1971, Precambrian apparent polar wandering; evidence from North America: Earth and Planetary Science Letters, 10(2), 273-280.

Timmons, J.M., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., Heizler, M.T., 2001, Proterozoic multistage (ca. 1.1 and 0.8 Ga) extension recorded in the Grand Canyon Supergroup and establishment of northwest- and north-trending tectonic grains in the southwestern United States, Geological Society of America Bulletin 113, pp. 163–180.

Torsvik, T. H., Voo, R. V. d., Preeden, U., Niocaill, C. M., Steinberger, B., Doubrovine, P. V., Hinsbergen, D. J. J. v., Domeier, M., Gaina, C., Tohver, E., Meert, J. G., McCausland, P. J. A., and Cocks, L. R. M., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, v. 114, p. 325-368.

Van de Kamp, P.C., 2016, Potassium Distribution and Metasomatism In Pelites and Schists: How and When, Relation To Postdepositional Events. *Journal of Sedimentary Research, 86*(6), 683-711.

Walker, T.R., Larson, E.E. & Hoblitt, R.P., 1981, Nature and origin of hematite in the Moenkopi Formation (Triassic), Colorado Plateau; a contribution to the origin of magnetism in red beds: Journal of Geophysical Research, vol. 86, pp. 317-333.

Wallmann, K., 2001, Controls on the cretaceous and Cenozoic evolution of seawater composition, atmospheric CO2 and climate: Geochimica et Cosmochimica Acta, vol. 65, no. 18, pp. 3005-3025.

Wernicke, B.P., Axen, G.J., and Snow, J.K., 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738- 1757.

West, A.J., Galy, A. & Bickle, M. 2005, Tectonic and climatic controls on silicate weathering: Earth and Planetary Science Letters, vol. 235, no. 1-2, pp. 211-228.

Williams, G.E., Schmidt, P.W., & Young, G.M., 2016, Strongly seasonal Proterozoic glacial climate in low palaeolatitudes: Radically different climate system on the pre-Ediacaran Earth. Geoscience Frontiers, 7(4), 555-571.

Zijderveld, J. D. A., 1967, A.C. Demagnetization of rocks: Analysis of results, in Collison, D. E., K.M. Creer, and Runcorn, S. K., eds., Methods in Paleomagnetism: New York, El Sevier Science, p. 254-286.

Chapter 2: Paleomagnetic and Petrographic Analysis of an Unconformity Surface in the Butler Hill Caldera, SE Missouri

GEOLOGIC BACKGROUND AND PREVIOUS WORK

The St. Francois Mountains (SFM) region of southeast Missouri is well known as a “Great Unconformity” location, wherein Proterozoic granite and rhyolite are overlain by Upper Cambrian sandstone and carbonate, with gaps of nearly one billion years’ duration (Fig. 1). The surface between the igneous basement and sedimentary cover was exposed for several hundred million years (Thacker and Anderson, 1977; Houseknecht and Ethridge, 1978) and therefore presents an additional location to study the effects of subaerial exposure and climatic conditions on silicate basement rocks using paleomagnetic methods.

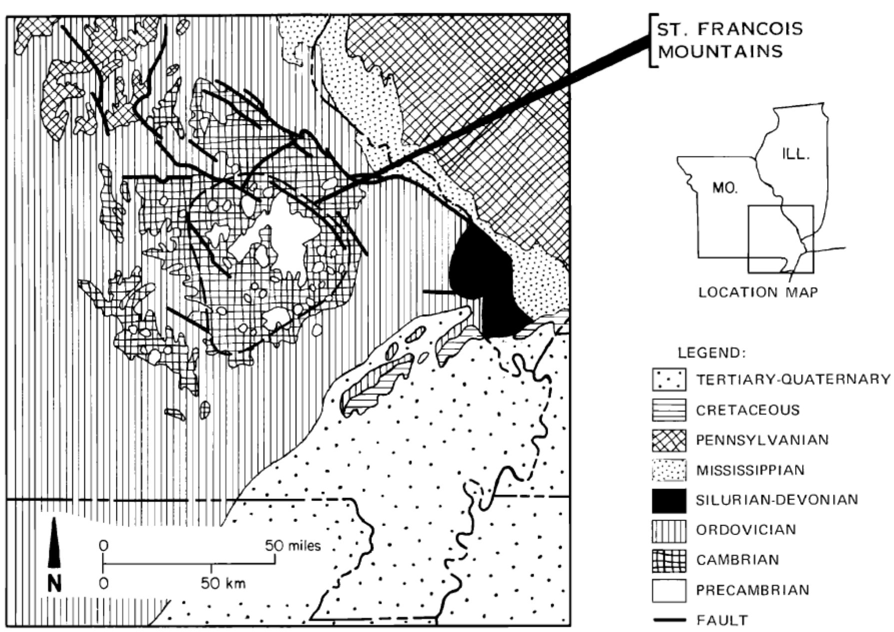


Figure 1 - Simple geologic map of southeast Missouri and the SFM area. Figure from Thacker and Anderson (1977).

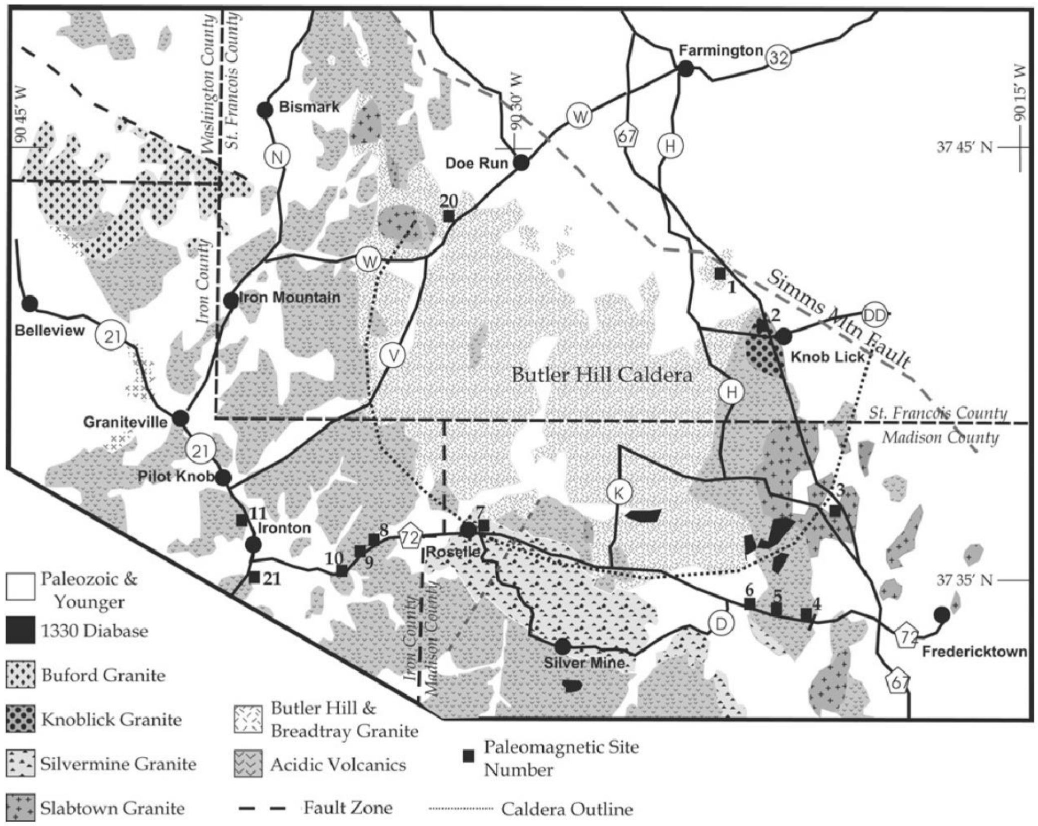


Figure 2 - Butler Hill Caldera and associated geologic units. Paleomagnetic site number 4, in the southeastern part of the map, coincides with sampling location for the Grassy Mountain Ignimbrite in this study. Figure modified from Meert and Stuckey (2002).

Exposed Precambrian rocks in the SFM form the heart of the Ozark dome uplift area and consist predominantly of units within the Butler Hill Caldera (BHC) (Fig. 2). The BHC is a complex combination of A-type granites and rhyolitic ignimbrites that covers almost 40,000 km^2 in the subsurface (Kisvarsanyi, 1980; Lowell, 1991). Initial volcanic activity in the caldera occurred approximately 1,476 ± 16 Ma and created the volcanic unit sampled for this study, the Grassy Mountain Ignimbrite (GMI) (Kisvarsanyi, 1980; Sides, 1980; Sides et al., 1981). Radiometric dating by Bickford and Mose (1975) confirms this timeframe for silicic lava eruptions. Towards the end of volcanism, degassing of the magma chamber allowed for ascension of the parent magma body and roof-down crystallization, which formed the plutonic unit this work discusses, the Butler Hill Granite (BHG) (Kisvarsanyi, 1980; Sides et al., 1981). By the Upper Cambrian, erosion had created variable relief in the region. Sea level then rose to cover the region for the first time in nearly one billion years (Thacker and Anderson, 1977). This led to patchy deposition of the Upper Cambrian Lamotte Sandstone in paleotopographic lows, which contains a localized basal boulder bed (Fig. 3) and cross-bedded quartzarenite and local arkose (Thacker and Anderson, 1977; Sutton and Maynard, 1996). Subsequent continued sea level rise led to the deposition of the Cambrian Bonneterre Formation, a series of dolomite units which rest conformably on the Lamotte, or unconformably on the basement where the Lamotte was absent.

Structurally, uplift and accompanying subsidence in the area led to the formation of the Ozark dome beginning in the Late Precambrian and continuing into the Mississippian. Some of the still-exposed Precambrian rocks may have undergone slight immersion but deposition was spotty and thin. The present-day core of the SFM area has undergone severe and prolonged erosional episodes since the Mississippian to remove any overlying sediment and re-expose the Precambrian rocks that may have been covered (Thacker and Anderson, 1977).

During the Pennsylvanian and Permian, the Ouachita-Marathon orogeny compressed rocks west and south of the SFM area, leading to the northward

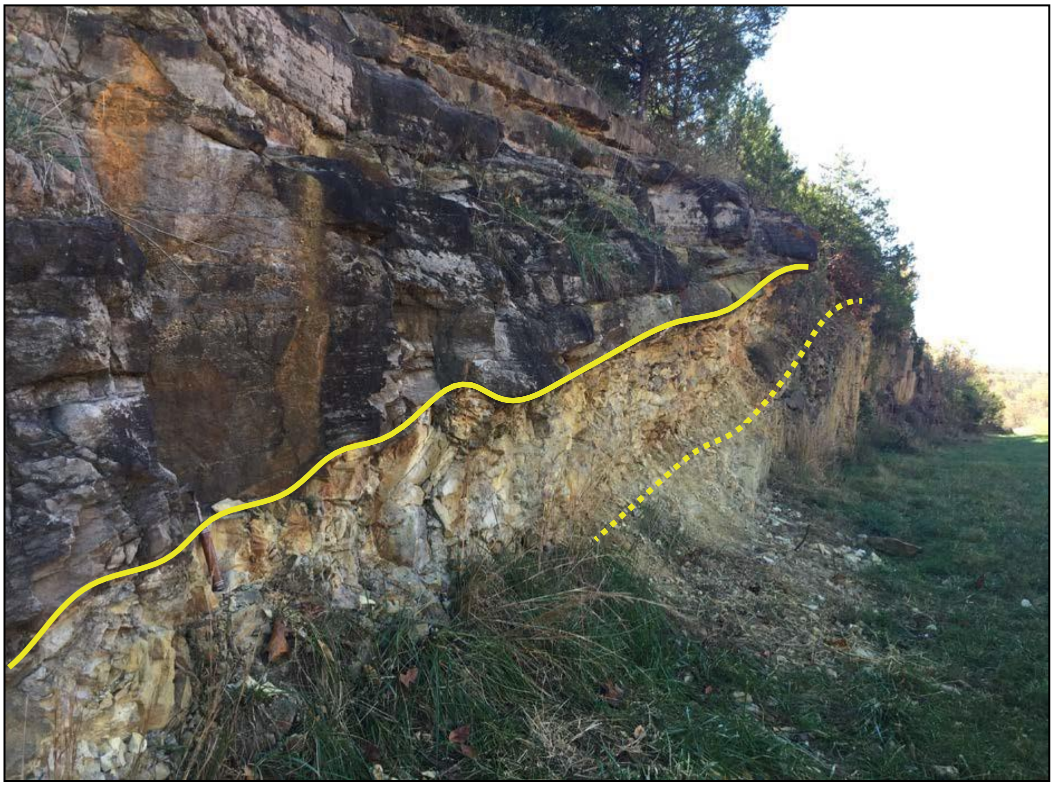


Figure 3 - Outcrop photo along Highway 72. Lamotte sandstone above solid line and basal boulder bed between solid and dashed line. The dashed line is approximately the unconformity surface atop the Grassy Mountain Ignimbrite. Boulder bed is approximately one meter thick.

movement of hydrothermal fluids in the subsurface (Sutton and Maynard, 1996; Appold and Garven, 1999). These warm fluids deposited Pb-Zn-Cu ores in the region while moving through the Cambrian sediments, possibly contacting the basal Lamotte and Bonneterre formations. Fluids influenced by ore-forming processes in these units may have also travelled downwards into the uppermost basement rocks, resulting in alteration of the crystalline basement (Sutton and Maynard, 1996). The basement is also likely to have been altered in some places by older Precambrian mineralization and K-metasomatism (Brown et al., 1989; Duffin, 1989; Smith et al. 1993; Sutton and Maynard, 1996).

Geochemical work on the crystalline basement rocks in the SFM began early in the 1960s with Rb-Sr dating of the BHC by Muehlberger et al. (1966). Braxland (1974) studied the chemical weathering of the unit and found that biotite weathered into hematite, indicating internally-sourced iron for iron oxides. Sutton and Maynard (1996), using geochemical and petrographic methods, reported pre-Lamotte alteration of crystalline basement rocks in the SFM area, with decreasing alteration as distance from the unconformity increased. They also indicated that post-Lamotte hydrothermal events produced several series of mineralizations resulting in hematite, calcite, biotite, and other minerals (Sutton and Maynard, 1996). Lowell (1991) discussed degradation of primary Fe-bearing minerals to Fe-oxides and chlorite accompanying secondary plagioclase in ignimbrites in the BHC. Lowell (1991) also noted sericitization of all feldspars and chlorites within granites in the region.

Previous paleomagnetic work in the SFM area has been reported by multiple workers beginning with Hays and Scharon (1966) and Hsu et al. (1966). These authors used structurally- uncorrected AF demagnetization to uncover near-equatorial paleopoles at 214.4°E and 219°E longitudes (Meert and Stuckey, 2002). However, some authors note a maximum of 10° dip to the southwest that resulted from the collapse of the caldera (Lowell, 1991; Meert and Stuckey, 2002) and hence later studies (Kisvarsanyi, 1980; Lowell, 1991, Meert and Stuckey, 2002) use a tilt-correction when reporting paleopoles. Meert and Stuckey (2002) provide evidence that their calculated paleopole (13.2°S, 219.0°E; d_p = 4.7°, d_m = 8.0°), which includes data from specimens of GMI and BHG, is primary based on positive conglomerate, baked contact, and fold tests (2002). Their longitudes were similar to those from the previous workers, but tilt-correction yielded a southern latitude.

The Upper Cambrian Lamotte Sandstone has also been the subject of several previous paleomagnetic studies. Al-Khafaji and Vincenz (1971) first reported on the magnetic remanence held in Lamotte samples and found scattered poles in different outcrop localities. They interpreted Carboniferous and Late Cambrian poles residing in hematite that were coincident with different stratigraphic intervals within the Lamotte (1971). Later, Wisniowiecki and Van der Voo (1981) reported Late Cambrian directions in some Lamotte and Bonneterre samples while stating that earlier reported paleopoles were likely the result of vector addition of multiple magnetizations. They interpreted the remanences in their study to reside in hematite or goethite in the Lamotte and magnetite in the Bonneterre.

Like the Vishnu group and Tapeats Sandstone discussed in the first chapter of this work, the BHG/GMI contact represents a significant time gap that underwent subaerial exposure for an extended period of time prior to deposition of the overlying sedimentary package. Both locations were exposed to supergene fluids during the Late Precambrian/Early Cambrian and were subsequently flooded by rising sea levels. Unlike the Nevada location, the St. Francois Mountains were a known topographic high point during the onset of flooding and therefore provide a contrast to the mostly uniform flooding of the southern Nevada area. The BHG and GMI could have undergone enhanced chemical and/or mechanical weathering due to high relief (e.g. Riebe et al., 2004) and therefore may provide insight into the effects of local elevation differences on alteration and paleomagnetic remanence acquisition. In addition to exhibiting variable paleotopography, these rocks also could have been altered by later hydrothermal fluid passage. This is also in contrast to the Nevada rocks, which likely have not been altered by any basinal or hydrothermal fluids due to compressional tectonic forces. When we consider the similar lithologies, ages, and timing of exposure, these two suites of rocks may provide a more direct comparison of alteration mechanisms and paleomagnetic signal in compressional and extensional deformation settings.

METHODS

Samples of Proterozoic basement rocks and Cambrian Lamotte Sandstone were collected near and at their common unconformities near the towns of Fredericktown and Farmington, Missouri (Fig. 4). Approximately 5 km west of Fredericktown on State Highway 72, the basement rock is the Proterozoic Grassy Mountain Ignimbrite. Two sites of ignimbrite (GMR1, 2) were drilled in place using a gasoline-powered portable modified chainsaw with a Pomeroy drill and oriented using a Brunton compass and inclinometer prior to extraction. Due to the extreme hardness of the rock, further samples were collected from three slabs (GMR3, 4, 5) obtained from the same location. Samples were taken from the slabs by orienting the slabs in the field with the Brunton compass and then drilling normal to the oriented surface using a water-cooled drill press in the sample preparation lab at the University of Oklahoma. Sites range from 6-23 samples per site.

Using the same portable drill at the same location, samples were collected from the overlying Lamotte Sandstone (GMS1, 2, 3; 8-10 samples per site) and from multiple clasts inside a conglomeratic boulder bed between the Lamotte Sandstone and Grassy Mountain Ignimbrite (GMC1; 13 samples from 6 clasts). All samples were oriented in the field prior to extraction.

Approximately 8.5 km south of Farmington, along US Highway 67, basement Butler Hill Granite outcrops beneath Lamotte Sandstone. Two sites of Butler Hill Granite samples (BHG1, 2; 10 samples per site) were obtained using the portable drill and oriented prior to extraction using the Brunton compass and inclinometer. Two sites of Lamotte Sandstone (LMS1, 2; 8-10 samples per site) were also collected at this location using the portable drill and oriented prior to extraction. Between the two locations, 49 samples of basement rock and 55 samples of sandstone and conglomerate were suitable for paleomagnetic analysis.

All samples were cut to standard 2.2 cm lengths and then measured for natural remanent magnetization (NRM) using a 2G Enterprises three-axis cryogenic magnetometer with DC SQUIDS. All suitable specimens were then subjected to thermal demagnetization in a stepwise fashion using an ASC Model TD-48 SC thermal demagnetizer, up to temperatures of 680-700°C in 20-25°C increments.

Paleomagnetic analyses were completed using the SuperIAPD program (http://www.geodynamics.no/resources.html). Data were plotted on orthogonal

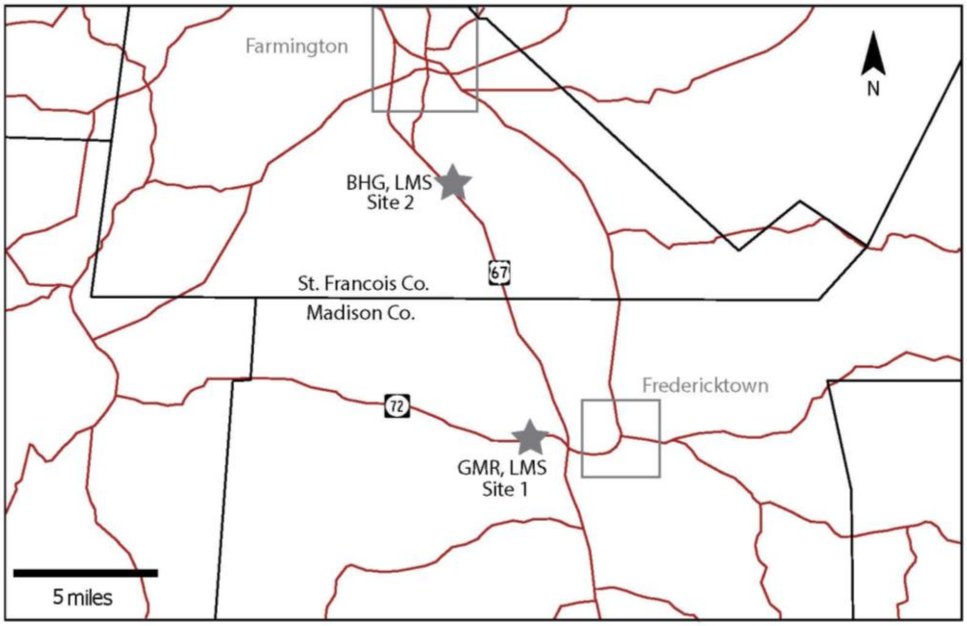


Figure 4 - Paleomagnetic sample collection sites in Missouri. BHG - Butler Hill Granite; LMS - Lamotte Sandstone; GMR - Grassy Mountain Ignimbrite; GMS - Lamotte Sandstone.

plots representing inclinations and declinations of the samples according to Zijderveld (1967) and then analyzed for magnetic components using principal component analysis (PCA) according to Kirschvink (1980). Components selected for further analysis and interpretation demonstrated mean angles of deviation (MAD) of less than 18°, although most specimens had MAD values less than 12°. Site means were computed using Fisher (1953) statistics.

Five specimens (three Lamotte and two igneous) were imparted with an isothermal remanent magnetization (IRM) at room temperature to help determine magnetic mineralogy. All specimens were first subjected to AF demagnetization at 120 mT to remove any existing remanent magnetization. Using an ASC Scientific impulse magnetizer, an IRM was then imparted in a stepwise fashion from 0 to 2500 mT and their resulting magnetizations were analyzed for magnetic mineral behavior.

Polished thin sections were prepared from two ignimbrites, two granites, five sandstones, and one conglomerate clast and analyzed using transmitted and reflected light for magnetic phases and textural relationships. Selected thin sections were analyzed using an FEI Quanta 250 Scanning Electron Microscope (SEM) with energy dispersive capabilities (EDS). Backscattered electron imaging (BSE) and EDS were used to aid in identification of magnetic phases and assist with textural relationship analysis.

RESULTS AND INTERPRETATIONS: PALEOMAGNETISM

Butler Hill Granite and Grassy Mountain Ignimbrite

Forty-nine samples of locally reddened granites and ignimbrites were collected from multiple stratigraphic intervals at two outcrops in the SFM area of southeast Missouri. Thermal demagnetization of specimens from five sites (BHG1, BHG2, GMR1, GMR2, and GMR3) removed two separate stable magnetic components. The first component (Fig. 5, Table 1), interpreted as the ChRM of the rocks, has a southwesterly declination and moderate down inclination after structural correction (D = 243.9°, I = 42.8°, N = 32, k = 122.3, α_{95} = 2.3°). This component was removed by 675°C in 14 GMR specimens and by 575°C in all other specimens of BHG and GMR. Magnetizations with maximum unblocking temperatures of greater than 575°C are interpreted to reside in hematite, while those with unblocking temperatures less than 575°C are interpreted to reside in magnetite. VGP calculations were performed on all site means (Fig. 6) containing this component and yielded a paleopole of 3.4°S latitude, 145.1°W longitude (d_p = 1.8°, d_m = 2.8°), which falls on the Mesoproterozoic portion of the APWP for North America (Fig. 10; Harlan et al., 2008). Structural correction was made to return overlying Lamotte bedding to horizontal: bedding attitude at the highway 72 outcrop was 038/07°E, while bedding at the US 67 outcrop measured 140/07°SW.

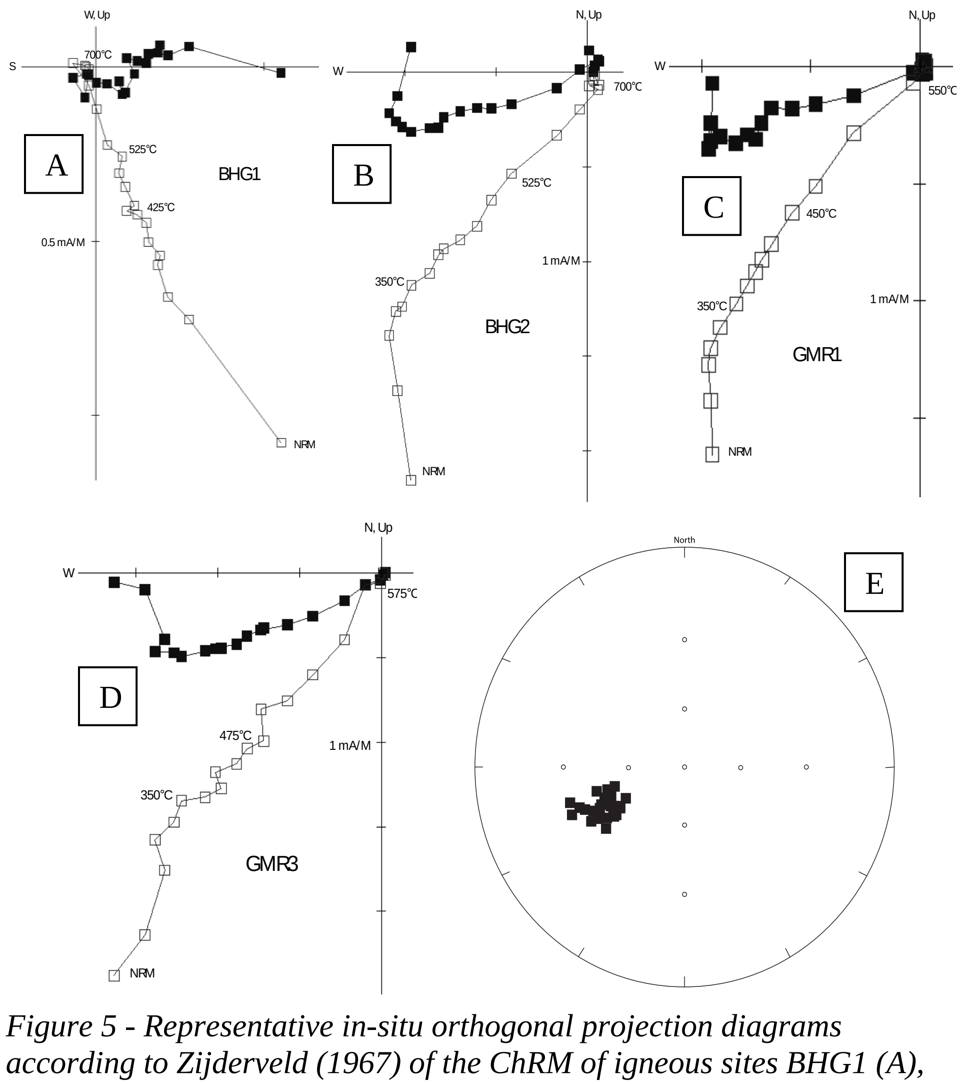


Figure 5 - Representative in-situ orthogonal projection diagrams according to Zijderveld (1967) of the ChRM of igneous sites BHG1 (A), BHG2 (B), GMR1 (C), and GMR3 (D). Southwesterly declinations (closed squares) and moderate down inclinations (open squares) are evident in all specimens. E: tilt-corrected equal area net of all specimens that exhibit the ChRM. Error circle too small to identify in figure.

Site(s)	Dec (°)	Inc (°)	N/N_o	*k*	α_{95}(°)	VGP Lat	VGP Long	D_p (°)	D_m (°)
<u>*Butler Hill Granite and Grassy Mountain Ignimbrite*</u>									
BHG1, 2	255.3	37.3	5/22	52.96	10.6	1.7	204.9	7.2	8.4
GMR1	245.0	46.1	13/13	132.45	3.5				
GMR3	240.7	41.6	14/14	325.08	2.2				
Mean	*243.9*	*42.8*	*32/49*	*122.3*	*2.3*	*S3.4°*	*W145.1°*	*1.8*	*2.8*
<u>*Lamotte Sandstone*</u>									
LMS1	137.3	44.1	6/10	31.15	12.2				
LMS2	150.1	53.7	1/7						
Mean	*138.9*	*45.6*	*7/17*	*33.02*	*10.7*	*N14.7°*	*W126.8°*	*8.7*	*13.6*

Table 1 - Site statistics for thermally demagnetized specimens from igneous and sedimentary rocks in SE Missouri. Igneous rocks yielded a magnetization that was removed prior to 675°C. Sedimentary rocks yielded a magnetization that was removed prior to 575°C. Declination and inclination (°) for magnetic directions. N/N_o represents total number of specimens used to calculate site mean with respect to total number of specimens measured in that site; precision parameter, k, represents grouping; α_{95} represents 95% cone of confidence around pole; virtual geomagnetic pole (VGP) latitude and longitude were calculated from declination and inclination; d_p/d_m represent major/minor ellipse axes of the 95% cone of confidence.

The second magnetic component removed from the igneous rocks was found in 14 samples of BHG and has a northwesterly declination and moderately steep down inclination after structural correction (D = 324.8, I = 69.8, N = 14, k = 67.49, α_{95} = 4.9°). This component was removed from the rocks by 350°C in most specimens, and is interpreted to reside in magnetite based on unblocking temperature. VGP calculation yields a paleopole situated at 61.1°N latitude, 135.4°W longitude (d_p = 7.2, d_m = 8.4), which does not plot on the APWP for North America (Torsvik et al., 2012). Rather, the moderately high latitude of the component and longitude to the east of the Cenozoic portion of the APWP indicate this could possibly be an effect of the Mesozoic and/or Cenozoic geomagnetic field on a certain population of magnetite grains, resulting in vector addition of magnetic directions.

Lamotte Sandstone

Forty-three samples of Lamotte Sandstone and twelve samples from conglomerate clasts within the basal boulder bed of the Lamotte were collected from the outcrops where igneous samples were taken. Thermal demagnetization of specimens from five sites (LMS1, LMS2, GMS1, GMS2, and GMS3) removed two stable magnetic components from the rocks. The first component (Fig. 6) was removed from nine specimens of GMS rocks from above the GMI outcrop and exhibits a northerly declination and moderately steep down inclination ($D = 2.3°$, $I = 67.6°$, $N = 9$, $k = 37.6$, $\alpha_{95} = 8.5°$). The component was removed by 425°C in all specimens and is interpreted to reside in magnetite. Calculation of a VGP for this component yields a paleopole of 83.4°N latitude and 75.8°W longitude, which suggests a modern influence on the pole and is therefore tentatively interpreted to represent a VRM acquired during the Cenozoic.

The second stable component (Figs. 6 and 7) in the Lamotte Sandstone was removed from seven specimens of LMS rocks from above the BHG outcrop and has a southeasterly declination and moderate down inclination after structural correction (D = 138.9°, I = 45.6°, N = 7, k = 33.02, α_{95} = 10.7°). The component was removed from all specimens by 575°C and is interpreted to reside in magnetite. VGP calculation produces a paleopole position of 14.7°S latitude and 53.2°W longitude

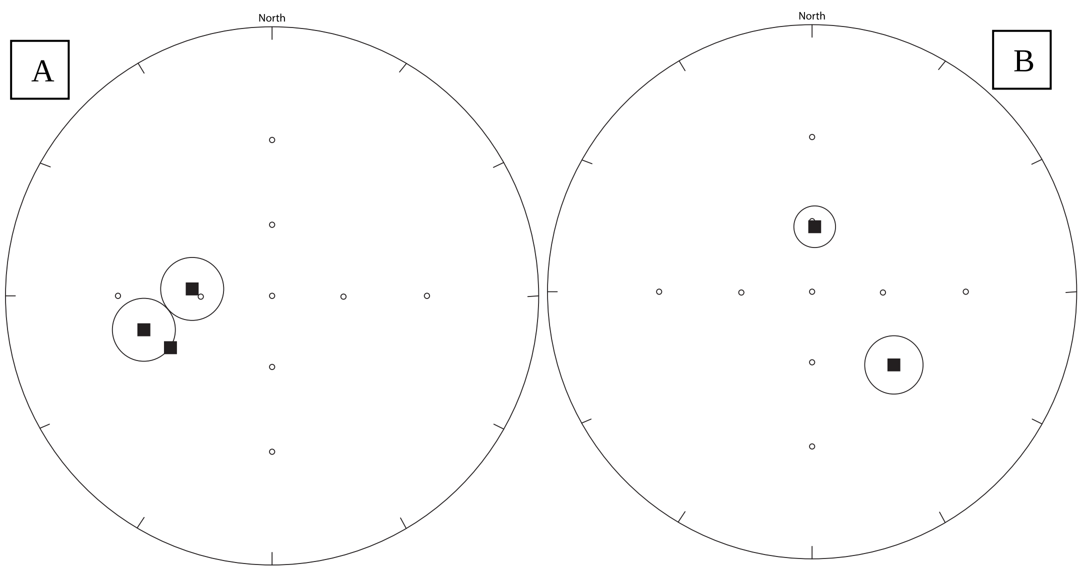


Figure 6 – A: tilt-corrected equal area projection of igneous site means that exhibit ChRM of southwesterly declinations and moderate down inclinations. B: tilt-corrected equal area projection of Lamotte sites showing modern VRM influenced component (northerly declination and steep down inclination) and ancient component (southeasterly declination and moderate down inclination). All sites shown with associated 95% confidence cones. Lack of a confidence cone indicates the α_{95} for the site is smaller than the square.

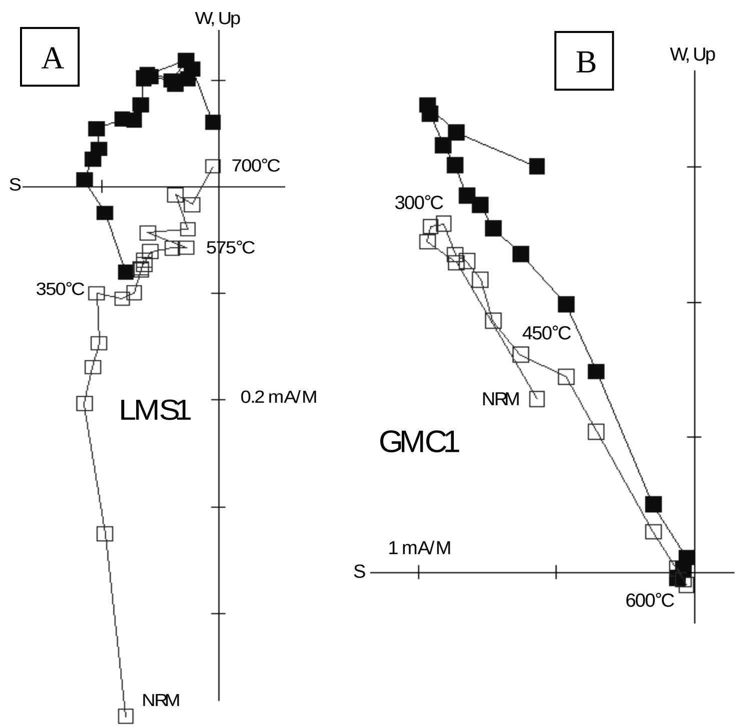


Figure 7 - Representative in-situ orthogonal projection diagrams according to Zijderveld (1967) of Lamotte site LMS1 (A) and basal boulder bed clast 5 (B). Open squares show inclination, closed squares show declination.

(d_p = 8.7°, d_m = 13.6°)—the antipode to this pole is 14.7°N latitude, 126.8°E longitude (Table 1) and plots on the Silurian portion of the APWP for North America (Fig. 9; Torsvik et al., 2012). The confidence ellipse for the pole encompasses part of the late Devonian to earliest Mississippian portion of the APWP—it is during that time that the magnetization likely was acquired.

A conglomerate test (Fig. 8) was performed on specimens collected from six clasts within the basal Lamotte boulder bed (site GMC). Five clasts with 2-3 specimens per clast and a specimen from a sixth clast were thermally demagnetized to 600°C and clast directions compared to determine the timing of magnetic acquisition. Stable magnetizations were removed from all clasts by 575°C—their directions were randomized (Fig. 8) and therefore pass the conglomerate test, indicating a magnetization acquired prior to deposition of the clasts. An additional magnetic component was removed from specimens in five of six GMC clasts at temperatures less than 350°C. This component exhibits a northerly declination and moderately steep down inclination (D = 9.1°, I = 63.3°, N = 10, k = 22, α_{95} = 10.5°) and is interpreted to reside in magnetite based on unblocking temperature. VGP calculation yields a paleopole of 80°N latitude and 50°W longitude (d_p = 13.1, d_m = 16.6) and represents the Modern viscous field.

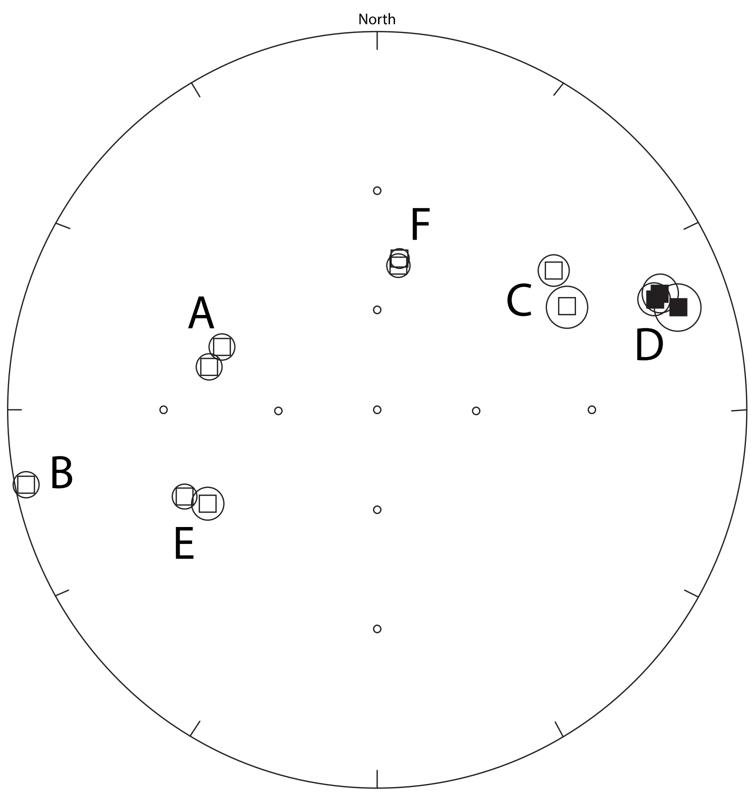


Figure 8 - Equal area projection of conglomerate test result for basal boulder bed at Grassy Mountain Unconformity site. Randomized clast magnetic directions indicate passage of the conglomerate test and therefore a pre-depositional acquisition of magnetic remanence. Open squares indicate negative inclinations, closed squares indicate positive inclinations.

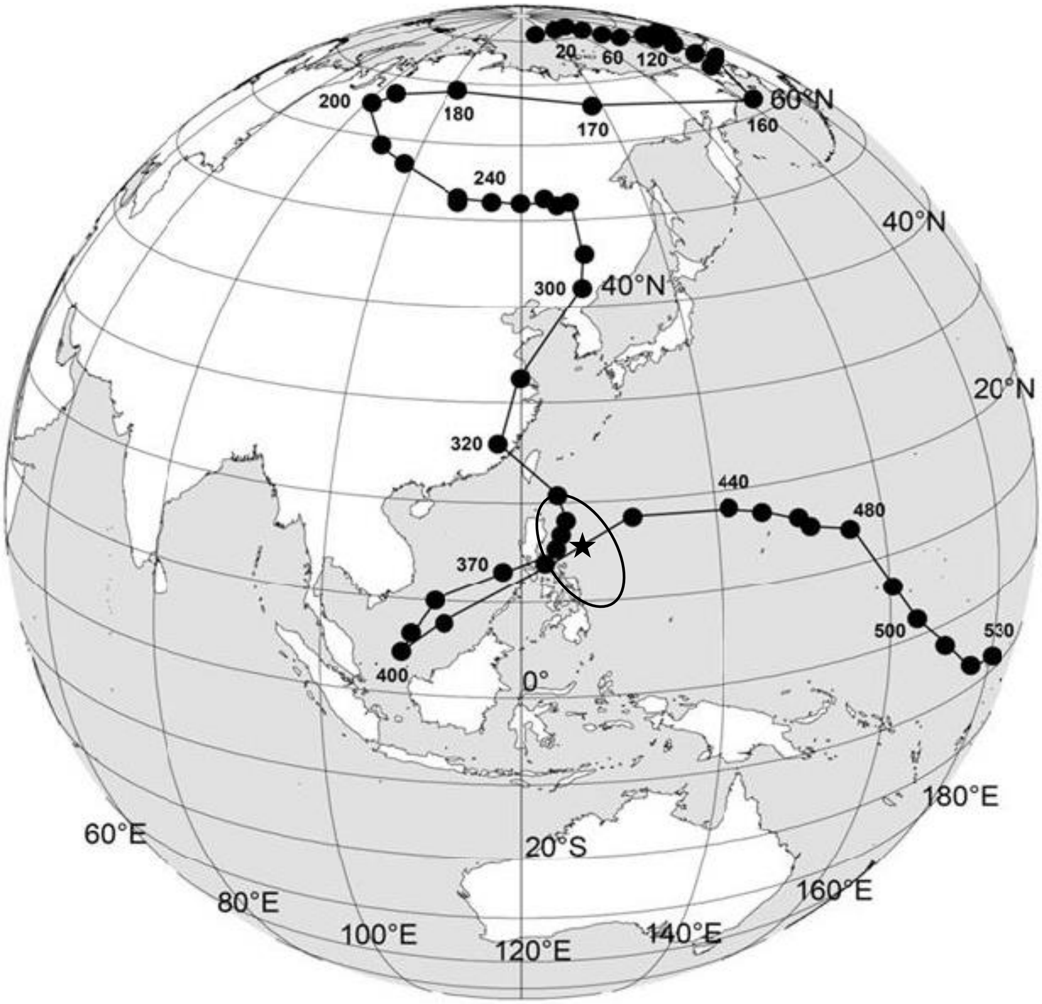


Figure 9 - Apparent polar wander path for North America (Torsvik et al., 2012). Star and associated confidence ellipse represent VGP for sites LMS1 and LMS2, on the Silurian portion of the path.

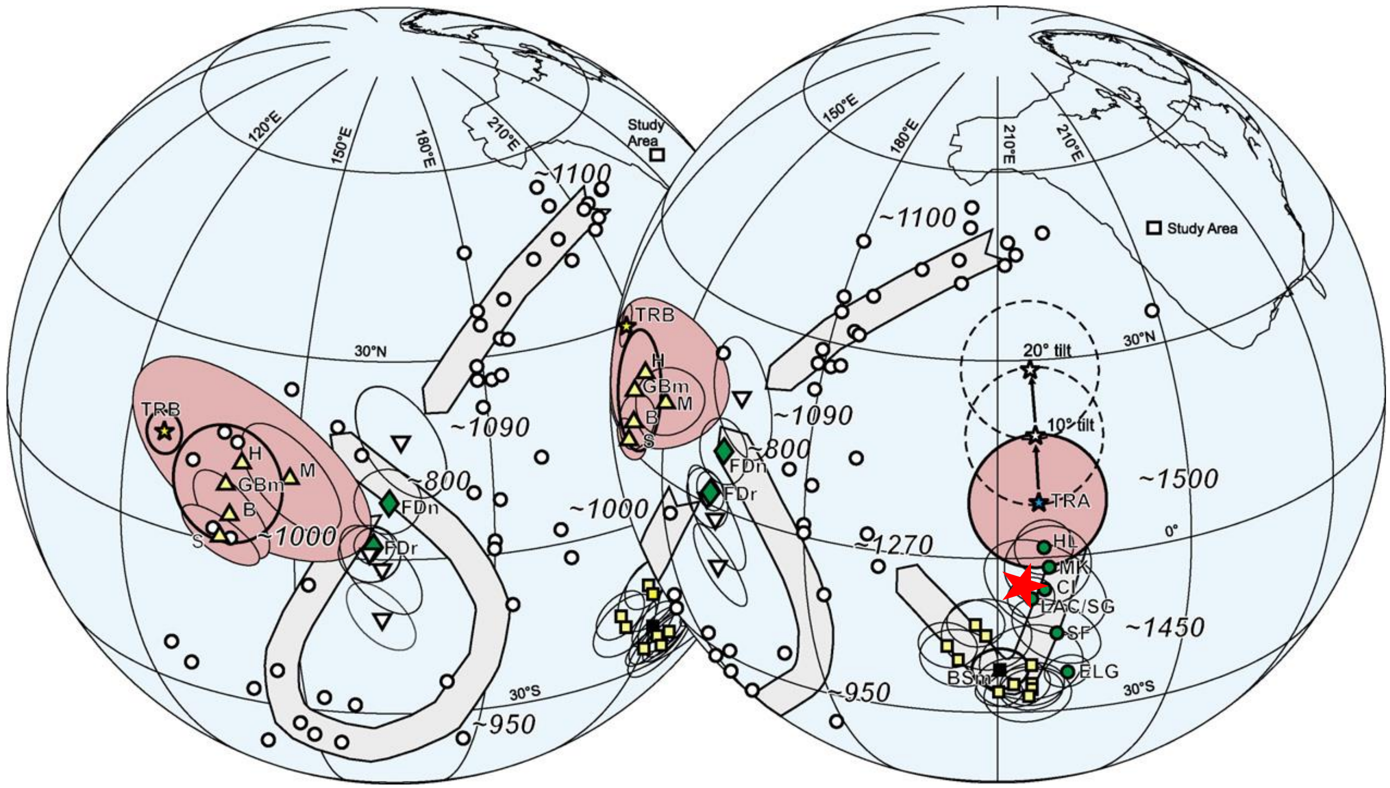


Figure 10 - Proterozoic apparent polar wander path for North America (Harlan et al., 2008). Red star indicates ChRM of BHG and GMI. Error ellipse (d_p/d_m = 1.8/2/8) smaller than star.

RESULTS AND INTERPRETATIONS: ROCK MAGNETISM

Two specimens of Lamotte sandstone, one conglomerate clast specimen, and two igneous specimens were imparted with an IRM under progressively stronger applied fields up to 2.5 Tesla. Acquisition behavior is consistent with the presence of multiple magnetic minerals, as most specimens exhibit both high and low coercivity behavior.

The GMI and one specimen from a conglomerate clast in the Lamotte boulder bed, which is composed of clasts of GMI, are both near saturation at low to mid-range applied fields (< 1000 mT). They both begin acquisition at low fields and appear to be mostly saturated by 350 mT (GMC 1-5; Fig. 11) to 500 mT and are interpreted to contain magnetite as the primary magnetic phase. This is consistent with paleomagnetic and petrographic evidence given in this work. One specimen of BHG shows continued acquisition at higher applied fields, indicating the presence of a high coercivity mineral such as hematite (BHG 2-11; Fig. 12). Two specimens of Lamotte sandstone exhibit differing behaviors—sandstone taken from above the BHG is not fully saturated by 2500 mT (LMS 1-2; Fig. 13a), while sandstone from above the GMI appears to be mostly saturated by approximately 500 mT (GMS 3-9; Fig. 13b).

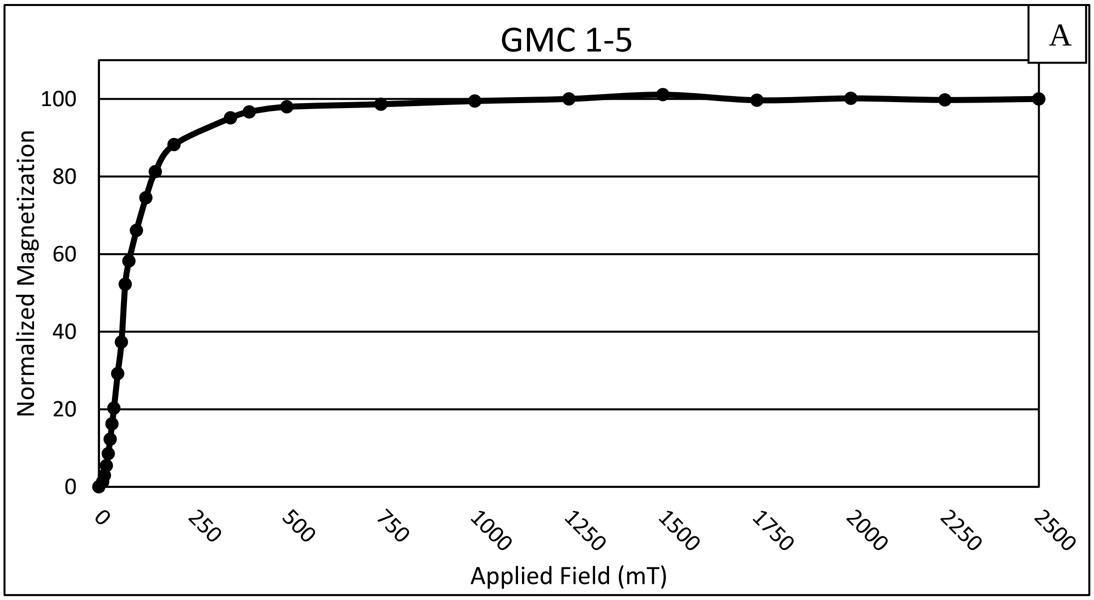


Figure 11 - IRM acquisition curve for a clast of GMI in the basal Lamotte boulder bed. Saturation is achieved at approximately 350 mT, indicating the presence of a low coercivity mineral phase.

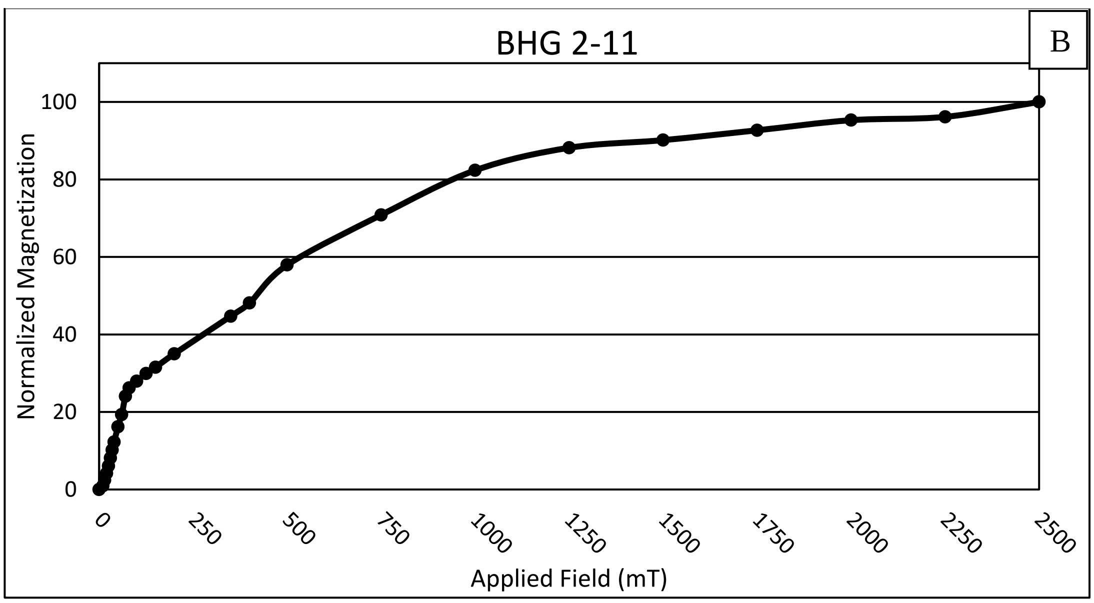
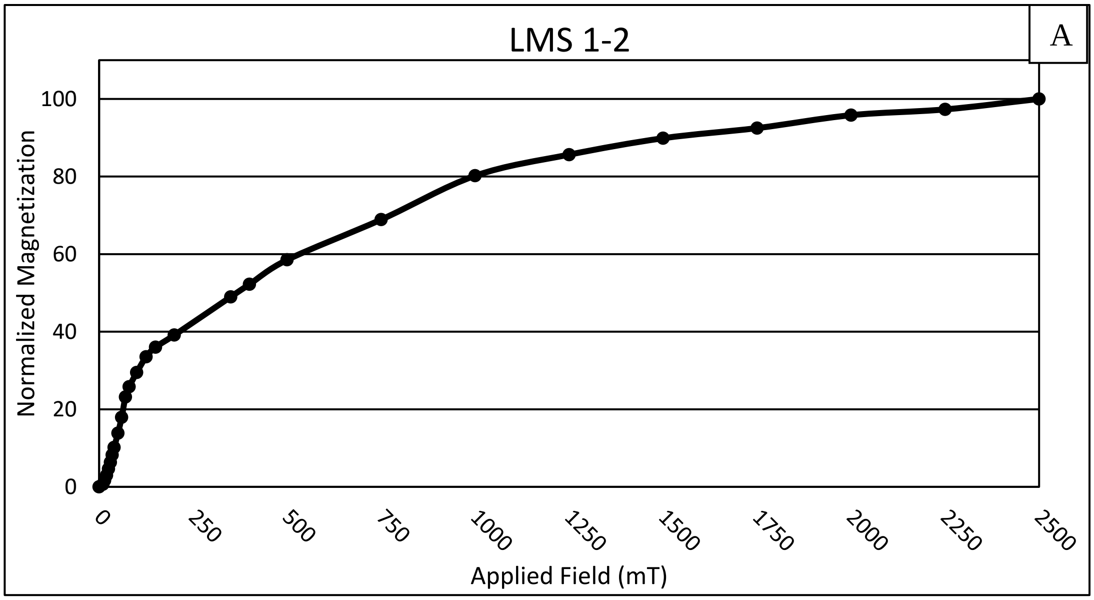


Figure 12 - IRM acquisition curve for BHG 2-11, displaying increasing saturation at higher applied fields and thus the presence of a high coercivity magnetic phase.



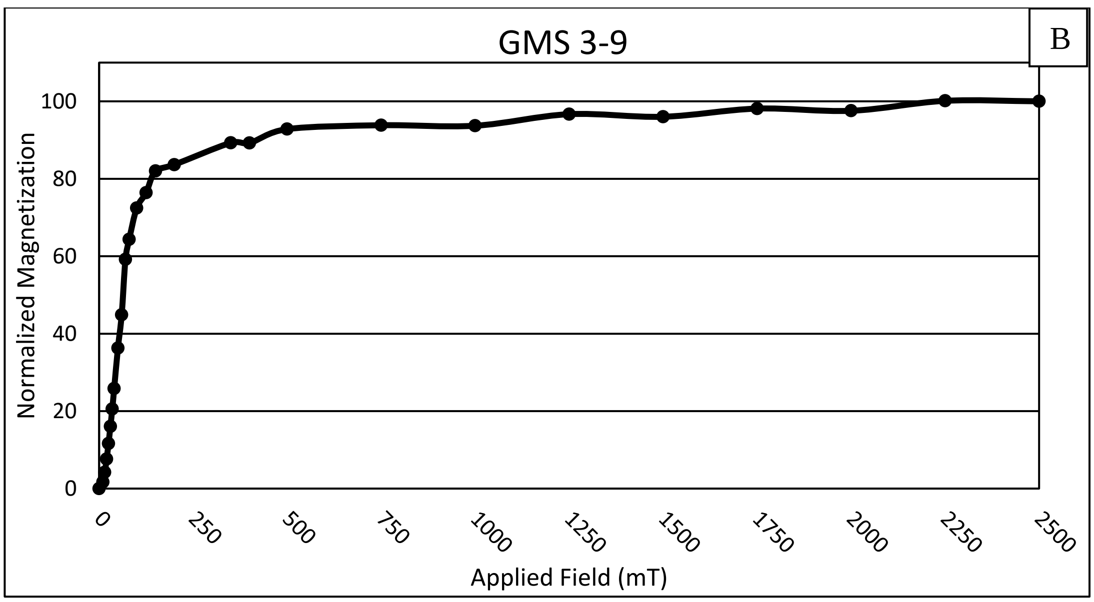


Figure 13 - IRM acquisition curves for Lamotte sandstone above the BHG (A) and the GMI (B). LMS 1-2 shows continued acquisition at high applied fields, indicating the presence of a high coercivity phase, while GMS 3-9 shows near-saturation by approximately 500 mT, indicating a dominant low coercivity phase.

RESULTS: PETROGRAPHY

Ten thin sections were prepared for study from the BHG, GMI, and Lamotte sandstone. In thin sections taken from near the unconformity (< 2 feet), the BHG is a quartz-alkali feldspar-plagioclase-biotite granite with localized granophyric texture. Composition of the plagioclase is approximately An_{10} to An_{15} based on extinction angles and EDS analysis. Accessory minerals include titanomagnetite (Fig. 14b), chlorite, apatite, and hematite. Radial chlorite and pigment hematite are found (Fig. 14a), typically associated with altered biotites and alkali feldspars. Moderate sericitization (Fig. 15b) of some plagioclase crystals is evident, but most plagioclase has retained its primary structure and twinning. Pigment hematite is seen in fractures (Fig. 15a), where internal reflections are diagnostic in reflected light.

The GMI is a devitrified rhyolitic ignimbrite with a quartz-alkali feldspar groundmass and subhedral to euhedral quartz, alkali feldspar, plagioclase, and accessory titanomagnetite phenocrysts. Most phenocrysts exhibit rapid cooling textures at the rim followed by well-developed internal structure—titanium and iron are exsolved in most magnetite crystals (Figs. 16a, 16c). There is little to no indication of sericitization of feldspars or heavy fracturing throughout the ignimbrite—fracturing tends to be localized and non-pervasive. Some hematite pigment is seen in small fractures in reflected light (Fig. 16b), often accompanied by pyrite.

The basal boulder bed of the Lamotte consists of variable sized clasts of GMI. Feldspars are preserved in clasts of GMI as they are in the ignimbrite itself and exhibit little difference other than minor fracturing. The lower Lamotte Sandstone at the Grassy Mountain outcrop consists of relatively poorly-sorted, coarse-grained subarkoses with dolomite and minor detrital Fe-oxides (Figs. 17a, 17b). Several apatite-replaced graptolite fossils (Fig. 18) are found in one thin section, typically

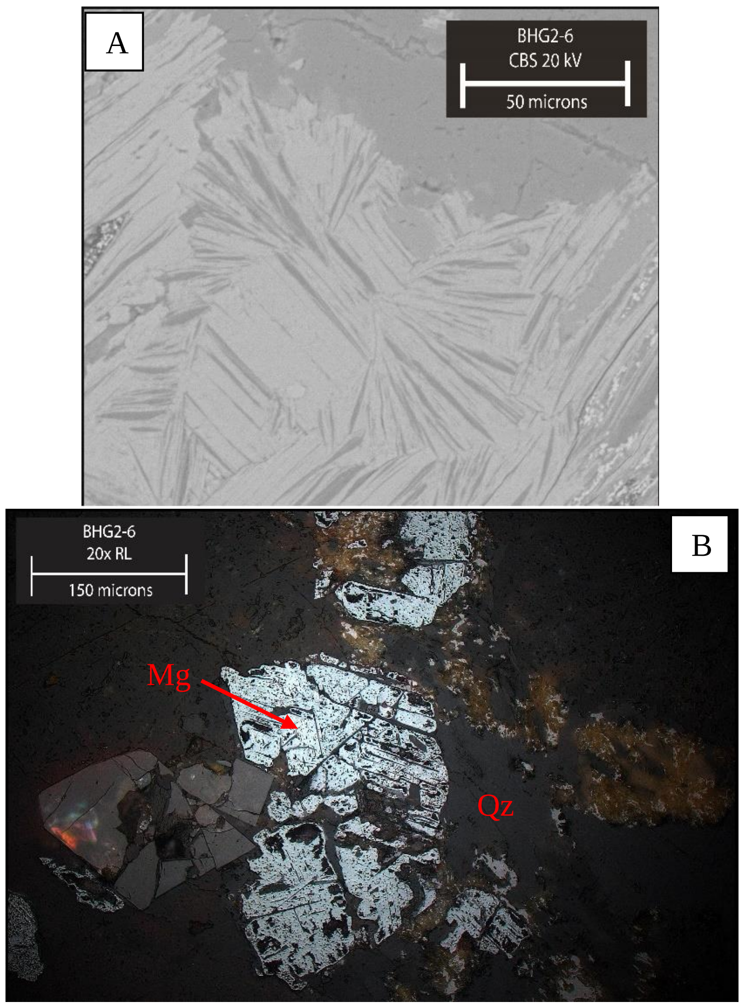


Figure 14 - A: SEM backscattered image of chlorite in a radial habit in BHG. B: Titanomagnetite (highly reflective) in BHG exhibiting exsolution of titanium. Reflected light.

less than one millimeter in length. Dolomite abundance and fossil evidence suggest that the rocks overlying the GMI are likely a transitional unit of the Lamotte Sandstone and Bonneterre Formation. Abundant pyrite is found throughout the unit (Figs. 17b, 17c). Lamotte samples overlying the BHG are well-sorted, fine-grained quartzarenites with silica, Fe-oxide, and clay cement (Figs. 17c, 17d).

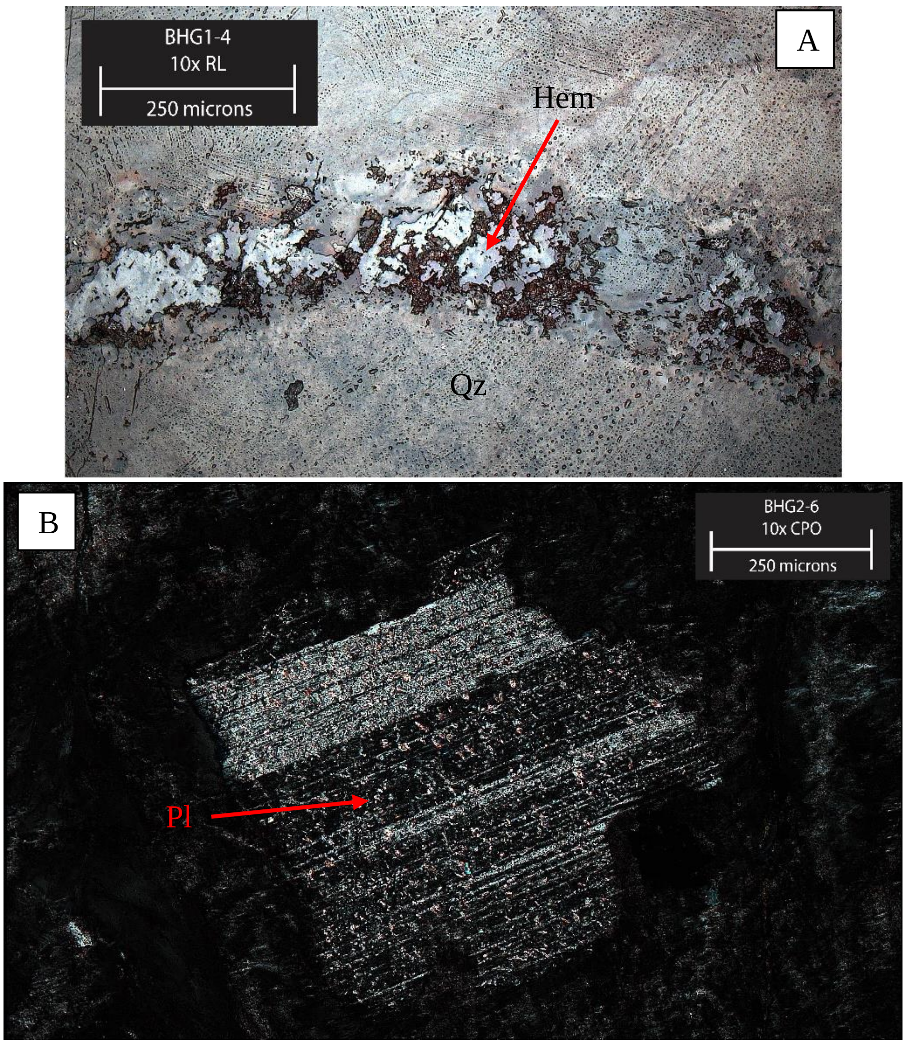


Figure 15 - A: Hematite in BHG with slight red internal reflections. Reflected light. B: Slight sericitization of plagioclase in BHG. Note majority of internal structure and twinning remains intact. Crossed nicols.

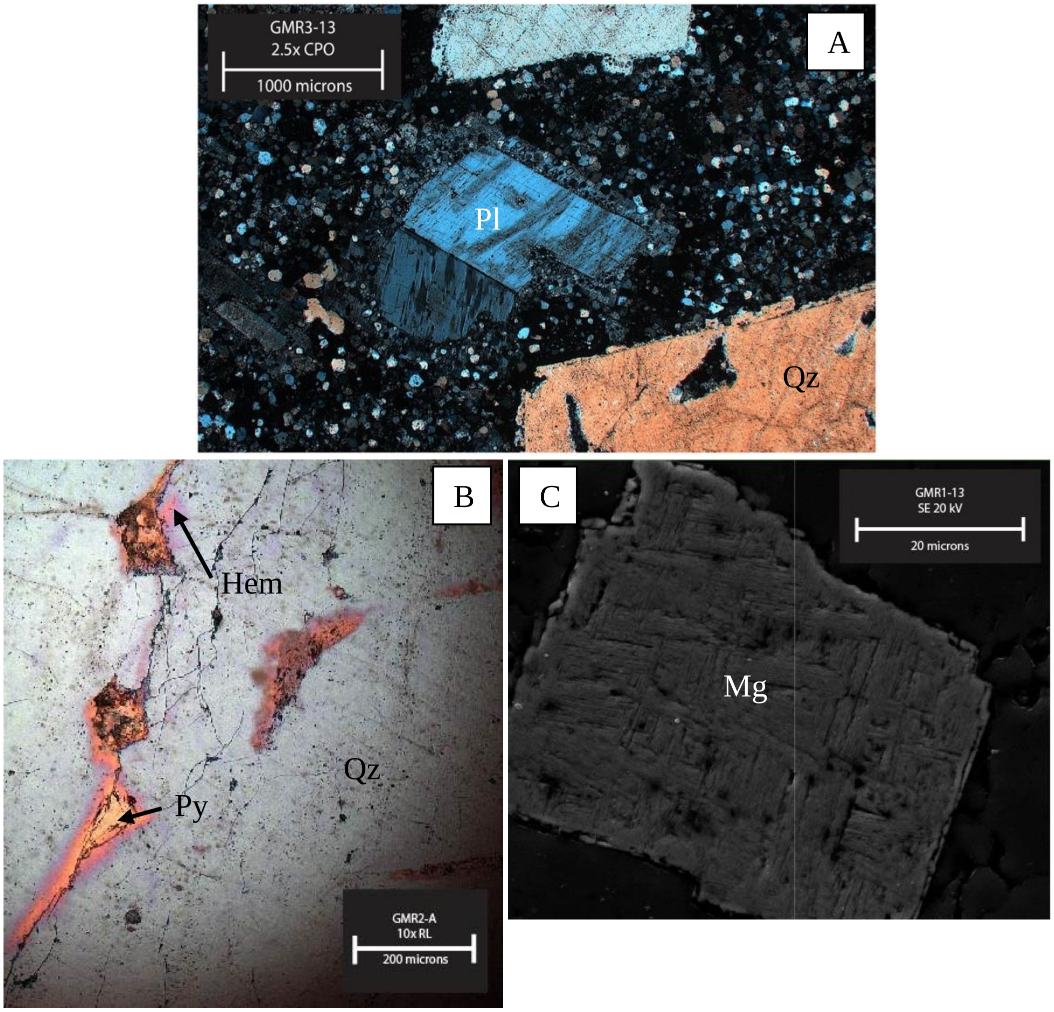


Figure 16 - Grassy Mountain Ignimbrite. A: Typical texture of GMI with aphanitic silica-alkali feldspar groundmass and euhedral to subhedral phenocrysts. Crossed nicols. Note lack of sericitization in plagioclase. B: Reflected light photomicrograph of a fracture in ignimbrite with red internal reflections of hematite. C: SEM secondary electron image showing exsolution of titanium and iron in magnetite in ignimbrite.

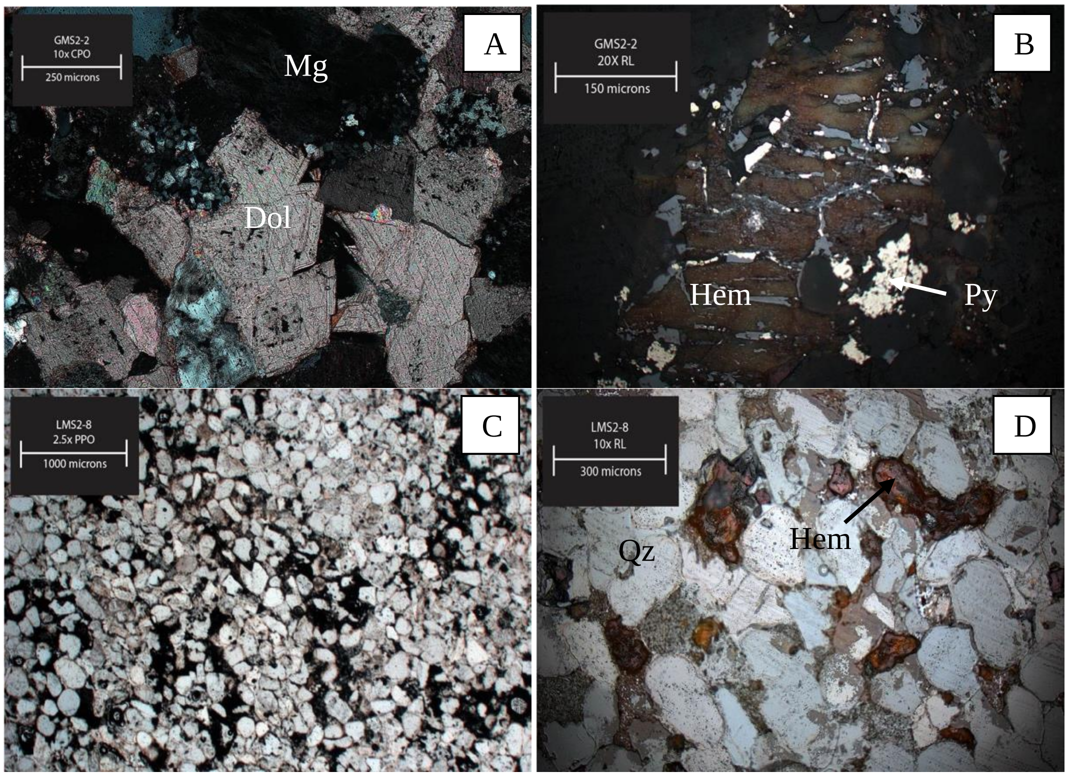


Figure 17 - Photomicrographs of Lamotte sandstone. A: sandstone above GMI with dolomite cement. Opaques are clay and Fe-oxide. Crossed nicols. B: reflected light showing hematite (red internal reflections) and highly reflective pyrite replacing another grain. C: sandstone above BHG with abundant opaques (clays, pyrite, Fe-oxide). Plane light. D: reflected light showing hematite (red internal reflections) and quartz overgrowths.

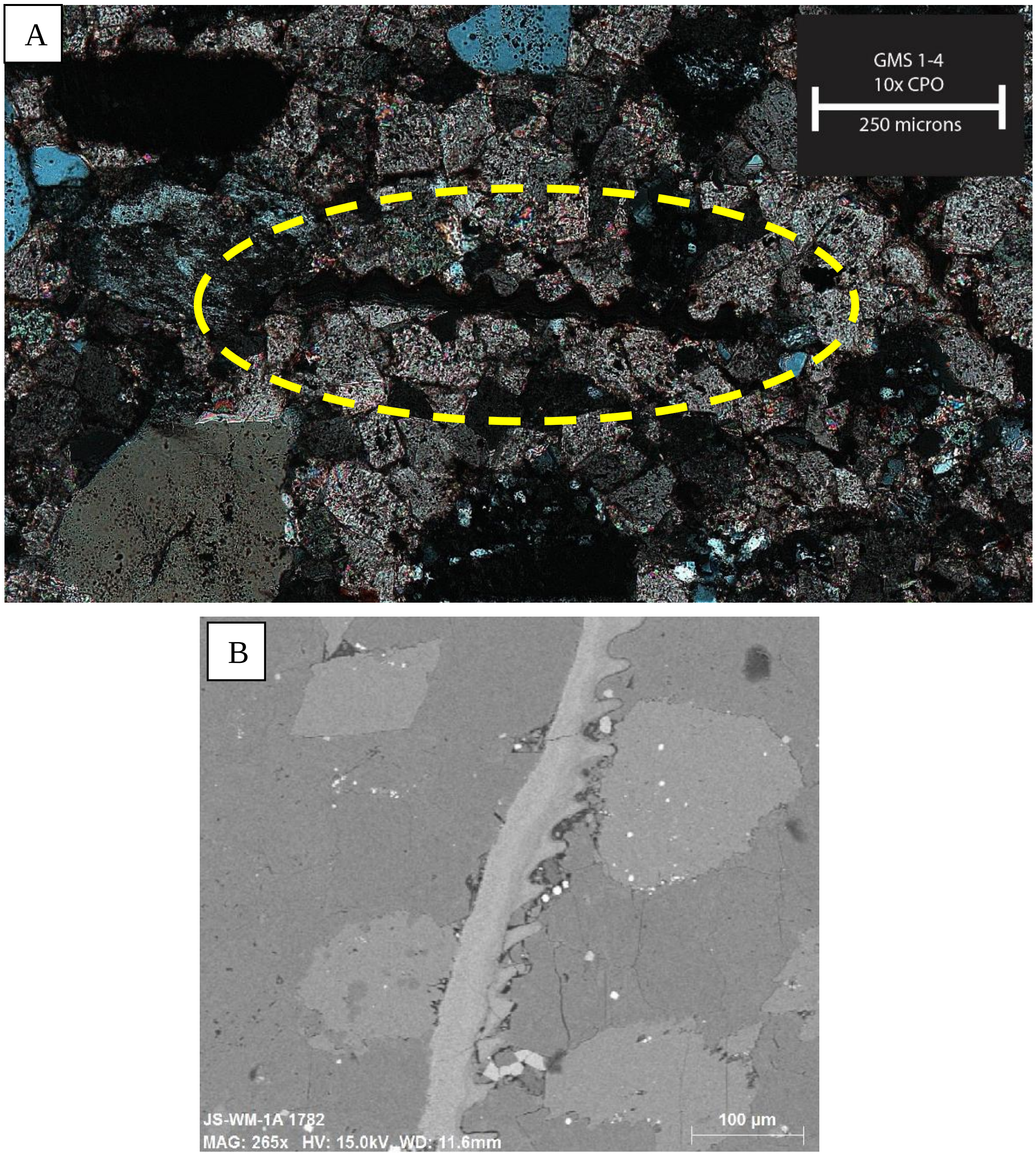


Figure 18 - A: Photomicrograph of apatite-replaced graptolite fossil within Lamotte-Bonneterre transition zone overlying the GMI. 10x magnification, crossed nicols. B: SEM secondary electron image of another graptolite fossil within the same unit.

DISCUSSION

Butler Hill Granite and Grassy Mountain Ignimbrite

The 1,476 ± 16 Ma BHG and GMI carry a ChRM residing in magnetite (GMI and BHG) and hematite (BHG), consistent with the findings of Meert et al. (2002) and earlier workers (Hsu et al., 1966, and Hays and Scharon, 1966). Unblocking temperatures ranging from 550°C-675°C, IRM acquisition data, and the presence of minor hematite in thin sections of BHG and magnetite in both rock types support this interpretation. The magnetization in magnetite is interpreted to be a primary thermoremanent magnetization acquired during eruption/emplacement and subsequent crystallization of the minerals during the Proterozoic, based on previous studies (Hsu et al., 1966, and Meert et al., 2002) and a positive conglomerate test performed on clasts of GMI within the basal boulder bed of the Lamotte at the Grassy Mountain outcrop. The less pervasive hematite magnetizations found in the BHG that carry similar directions are interpreted as chemical remanent magnetizations (CRMs) resulting from the precipitation of hematite from supergene fluids during pre-Lamotte weathering processes.

The interpretation of a primary magnetization for the igneous suite in this study indicates that surface conditions in the SFM region during time of subaerial exposure (Mesoproterozoic to Late Cambrian) were not conducive to the precipitation of hematite. Specifically, the lack of a secondary magnetization in hematite in GMI rocks suggests that surface rocks were not chemically weathered at a rate rapid enough to enable penetration of supergene fluids. This could be due to the high silica content (75-78 wt% SiO_2; Lowell, 1991) and initial vitrification of the silica-rich glass of the GMI, which would have presented a more weathering-resistant, low-permeability surface material and prevented accelerated mechanical/chemical weathering of any feldspars contained within the unit. Alternately, if a magnetization did exist prior to the deposition of the Lamotte or Bonnettere Formation, erosion likely removed any near-surface material that did contain a stable, non-primary magnetization.

The emplacement mechanism of the BHG and similar granites has been discussed by several previous workers (Hamilton and Myers, 1967; Thacker and Anderson, 1977; Sides, 1980; and Meert et al., 2002) and is summarized as a shallow, slightly tilted batholith that intruded the ejecta of less-evolved magmas of the same batholith. This emplacement mechanism likely limited the amount of BHG that was subaerially exposed for quite some time. Overlying silica-rich GMI rocks would have covered the intruding granites and prevented penetration of supergene fluids until erosion exposed the intrusive rocks. It is possible that a combination of the stratigraphic relationship between the intrusive and extrusive rocks and unfavorable climatic conditions after exposure of the feldspar-rich granite can explain the lack of a secondary magnetization in authigenic hematite. Although Sutton and Maynard (1996) reported pre-Lamotte alteration in the upper portions of the basement in five drill cores throughout the SFM, none of their cores encountered the GMI. This supports the hypothesis of the GMI acting as a barrier to alteration of underlying crystalline rocks, as the more phaneritic basement rocks without the overlying vitrified layer are known to be influenced by pre-Lamotte weathering processes (Sutton and Maynard, 1996).

Alteration of the basement granites has been reported (Braxland, 1974; Sutton and Maynard, 1996; Plymate et al., 2001; Driese et al., 2007) and attributed to *in situ* unconformity surface fluid movement in the subsurface and alteration of the basement through those means. Severe sericitization of plagioclase and mixed-layer clays from alkali feldspars are abundant in thin sections of BHG examined in this study. Some BHG samples contain minor chlorite and epidote, as well as minor fracture-fill hematite. The lack of late Proterozoic or later magnetizations in basement rocks in this study also suggests that these processes likely occurred after the subaerial exposure of the paleosurface and deposition of the overlying sedimentary package during the Paleozoic. This could have occurred during Ozark dome uplift and the subsequent northward movement of orogenic, sometimes ore-forming (Appold and Garven, 1999), fluids during the Ouachita-Marathon orogeny.

Paleotopography and the movement of fluids in different levels of the stratigraphy has also been suggested as a controlling factor in alteration and ore-forming processes. Appold and Garven (1999) recognized the importance of relief over the Ozark dome during the Ouachita-Marathon orogeny as a limiting factor in fluid conduction through the St. Francois aquifer, which includes the Lamotte and Bonneterre formations. Sutton and Maynard (1996) found variable degrees of alteration in uppermost St. Francois basement rocks that was correlated to paleotopographic features such as valley bottoms and plateaus.

Lamotte Sandstone

A magnetic component residing in magnetite and having southeasterly declination and moderate down inclination was removed from some specimens of basal Lamotte sandstone and is interpreted to be a remagnetization acquired during ore-forming hydrothermal fluid movement during the Late Devonian to Early Mississippian. Previous work has confirmed the presence of hydrothermal ore deposits throughout the St. Francois aquifer and their importance as a possible source of economic metals (e.g.; Thacker and Anderson, 1977; Brown et al., 1989; and Appold and Garven, 1999). Kish and Stein (1985) and Lange et al. (1983) describe a pervasive Mississippi Valley-Type (MVT) ore-forming hydrothermal event occurring at approximately 360 Ma, citing evidence from Rb-Sr isotope analysis from glauconite within the Cambrian strata in the Viburnum trend, which is situated on the northwest side of the St. Francois Mountains. These fluids were possibly heated by Middle Devonian alkaline igneous activity (Zartman et al., 1967), and may have been sufficiently hot to cause remagnetization of existing magnetite grains. Alternately, the remanence could be held in authigenic magnetite precipitated from dissolved Fe ions in the ore-forming fluids. Graptolite fossils found within the Lamotte-Bonneterre transition zone above the GMI could provide additional insight, as no Cambrian graptolites have been reported in the Lamotte or Bonneterre—only Late Ordovician (Marshall, 1971) and Late Silurian (Satterfield, 1972) graptolites have been reported in eastern Missouri, neither within the Cambrian rocks.

Sutton and Maynard (1996) indicate the presence of hematite in the Lamotte, which is corroborated by petrographic study in this work. However, hematite is not a carrier of a stable magnetic component in the rocks in this study area. It is possible that the early hematite formation discussed by Sutton and Maynard (1996) continued over time, leading to exposure to a changing magnetic field and a localized paleomagnetic signal similar to that found in the Tapeats sandstone in the first chapter of this work.

Al-Khafaji and Vincenz (1971) also reported a Carboniferous pole position from coarse-grained samples of the Lamotte Sandstone, although their latitude was more northerly (32°). They reported weak NRM values, which is supported by this study—NRM strengths of less than 1 mA/M were measured in most LMS samples. Both Vincenz et al. (1967) and Wisniowiecki and Van der Voo (1981) reported a remanence with a southeasterly declination and shallow positive inclination from samples of the Lamotte that were interpreted to be Late Cambrian, but the stratigraphic interval within the Lamotte is not specified in either work and hence the paleomagnetic results cannot be correlated with the results of this study.

Heavy hematite pigment stain is observed in some thin sections of LMS—this is restricted to LMS samples taken from above the BHG, which suggests that the iron source for hematite precipitation could be the granite itself. Extensive K-metasomatism has been reported in the BHG by several authors (Braxland, 1974; Sutton and Maynard, 1996; Plymate et al., 2001) and likely required fluid flow to facilitate the upward movement of ions, including iron. That upward movement could have mobilized iron within the granite and transported it to the more permeable, oxygenated Lamotte and triggered precipitation of hematite.

Hematite staining is largely absent from samples of LMS taken from above the GMI, suggesting that the GMI has not acted as a conduit for upward fluid migration into the Lamotte. This is consistent with the high-silica, low permeability nature of the ignimbrite, which was likely the dominant controlling lithology in paleoweathering processes in the region. The original vitrification of the ignimbrite probably prevented the majority of surficial and atmospheric processes from acting on the underlying BHG. This suggests that although paleotopographic differences and climatic patterns may have played a role, exposed bedrock lithology in the SFM area could have been one of the more, if not the most, important factor controlling mechanical and chemical denudation rates.

CONCLUSION

Like the previous chapter, work on the Butler Hill Granite, Grassy Mountain Ignimbrite, and Lamotte Sandstone in Missouri yielded inconclusive results for the initial question of whether paleoweathering surfaces can be characterized using paleomagnetic methods and if that information can help identify periods of increased chemical weathering. Paleomagnetic data from this study did not indicate hematite formation due to subaerial exposure prior to sedimentary deposition on the unconformity surface. Hematite present in the rocks is explained by other mechanisms, such as limited precipitation due to hydrothermal activity. Hematite is observed in thin section as pigment, but little to no specular hematite is visible.

The overlying Grassy Mountain Ignimbrite could have provided some protection for the more alteration-susceptible Butler Hill Granite during the timeframe when exposure should have enhanced chemical weathering. This stratigraphic relationship is likely the mechanism for the preservation of the primary magnetization interpreted in the GMI and BHG here. As such, we can conclude that the lithology of the exposed surface in the SFM area—more than elevation, climate, and atmospheric CO_2 levels—was a very important factor in controlling the amount of chemical weathering in the upper crystalline basement.

The Lamotte sandstone holds a Devonian-Mississippian magnetization that is likely due to hydrothermal fluid movement during ore formation, but it appears that these fluids, if they penetrated the basement, did not cause extensive precipitation of any new magnetic minerals or remagnetization of any existing magnetic phases in the basement. Still, the evidence given here for the Devonian-Mississippian remagnetization of portions of the Cambrian sedimentary strata suggest that paleomagnetism may be used to further constrain the timing of MVT-type ore-forming processes.

Like the Precambrian paleopoles found in Nevada, the Proterozoic poles found in this study indicate that any paleoweathering processes that led to the precipitation of hematite occurred prior to the Early Cambrian. The Proterozoic pole found in the GMI provides more evidence for resolving the APWP for the

Mesoproterozoic, but a more thorough understanding of the Neoproterozoic APWP must be realized to fully resolve the significance of the poles.

REFERENCES

Al-Khafaji, S. A., & Vincenz, S. A., 1971, The Magnetization of the Cambrian Lamotte Formation, Missouri: Geophys. J. R. Astr. Soc. 24, 175–205.

Appold, M. S., & Garven, G., 1999, The hydrology of ore formation in the southeast Missouri district; numerical models of topography-driven fluid flow during the Ouachita orogeny: Economic Geology and the Bulletin of the Society of Economic Geologists, 94(6), 913-935.

Bickford, M., & Mose, D., 1975, Geochronology of Precambrian rocks in the St. Francois Mountains, southeastern Missouri. *Geology*, *3*(9), 537-540.

Blaxland, A. B., 1974, Geochemistry and geochronology of chemical weathering, Butler Hill Granite, Missouri: Geochimica Et Cosmochimica Acta, 38(6), 843-852.

Brown, V.M., Kisvarsanyi, E.B., & Hagni, R.D., 1989, "Olympic Dam-type" deposits and geology of middle Proterozoic rocks in the St. Francois Mountains Terrane, Missouri: Society Econ. Geol. Guidebook Series, v. 4, 172 p.

Driese, S. G., Medaris, L. G., Ren, M., Runkel, A. C., & Langford, R. P., 2007, Differentiating pedogenesis from diagenesis in early terrestrial paleoweathering surfaces formed on granitic composition parent materials: Journal of Geology, 115(4), 387-406.

Duffin, M. E., 1989, Nature and origin of authigenic K-feldspar in Precambrian basement rocks of the North American midcontinent: Geology (Boulder), 17(8), 765-768.

Fisher, R., 1953, Dispersion on a Sphere: Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, v. 217, no. 1130, p. 295-305.

Hamilton, W., and Myers, W. B., 1967, The nature of batholiths: U.S. Geological Survey Professional Paper 554-C, p. CI—C30.

Harlan, S. S., Geissman, J. W., & Snee, L. W., 2008, Paleomagnetism of Proterozoic mafic dikes from the Tobacco Root Mountains, southwest Montana. Precambrian Research, 163(3-4), 239-264.

Hays, W. W., & Scharon, L., 1966, A paleomagnetic investigation of some of the Precambrian igneous rocks of southeast Missouri: Journal of Geophysical Research, 71(2), 553-560.

Hsu, I., Anderson, R. E., & Scharon, L., 1966, Paleomagnetic properties of some Precambrian rocks in Missouri: Journal of Geophysical Research, 71(10), 2645-2650.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: Geophysical Journal of the Royal Astronomical Society, v. 62, no. 3, p. 699-718.

Kisvarsanyi, E. B., 1980, Granitic ring complexes and Precambrian hot-spot activity in the St. Francois terrane, midcontinent region, United States: Geology (Boulder), 8(1), 43-47.

Lange, S., Chaudhuri, S., & Clauer, N., 1983, Strontium isotopic evidence for the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri. Economic Geology, 78(6), 1255-1261.

Lowell, G. R., 1991, The Butler Hill Caldera; a mid-Proterozoic ignimbrite-granite complex: Precambrian Research, 51(1-4), 245-263.

Marshall, F., 1971, Late Ordovician Graptolites from the Maquoketa Formation in Eastern Missouri. Journal of Paleontology, 45(2), 253-257.

Meert, J. G., & Stuckey, W., 2002, Revisiting the paleomagnetism of the 1.476 Ga St. Francois Mountains igneous province, Missouri: Tectonics, 21(2), 19.

Muehlberger, W. R., Hedge, C. E., Denison, R. E. and Marvin, R. F., 1966, Geochronology of the midcontinent region, United States. 3. Southern Area: J. Geophys. Res. 71, 5409- 5426.

Plymate, T. G., Kendall, J. D., Shepard, L. M., & Clark, K. C., 2001, Structural state of K- feldspar in the felsic volcanic rocks and ring pluton granites of the Butler Hill Caldera, St. Francois Mountains, southeastern Missouri: The Canadian Mineralogist, 39, Part 1, 73-83.

Riebe, C.S., Kirchner, J.W. & Finkel, R.C., 2004, Sharp decrease in long-term chemical weathering rates along an altitudinal transect: Earth and Planetary Science Letters, vol. 218, no. 3-4, pp. 421-434.

Satterfield, I., 1972, Late Silurian Graptolites from the Bainbridge Formation in Southeastern Missouri. Journal of Paleontology, 46(4), 492-498.

Sides, J. R., 1980, Emplacement of the Butler Hill Granite, a shallow pluton within the St. Francois Mountains batholith, southeastern Missouri: Geological Society of America Bulletin, 91(9), 535-540.

Sides, J. R., Bickford, M. E., Shuster, R. D., & Nusbaum, R. L., 1981, Calderas in the Precambrian terrane of the St. Francois Mountains, southeastern Missouri: Journal of Geophysical Research, 86, 10349-10364.

Smith, J.V., Steele, I.M., Banfield, J.F., & Hay, R., 1993, Diagenesis and formation of K-sanidine in Precambrian mafic rocks of the St. Francois Mts., Missouri: Geol. Soc. America Abs. with Prog., v. 25, p. A381.

Stein, H., & Kish, S., 1985, The timing of ore formation in Southeast Missouri; Rb-Sr glauconite dating at the Magmont Mine, Viburnum Trend. Economic Geology, 80(3), 739-753.

Sutton, S. J., & Maynard, J. B., 1996, Basement unconformity control on alteration, St. Francois mountains, SE Missouri: The Journal of Geology, 104(1), 55.

Thacker, J. L., & Anderson, K. H., 1977, The geologic setting of the southeast Missouri lead district; regional geologic history, structure and stratigraphy: Economic Geology and the Bulletin of the Society of Economic Geologists, 72(3), 339-348.

Torsvik, T. H., Voo, R. V. d., Preeden, U., Niocaill, C. M., Steinberger, B., Doubrovine, P. V., Hinsbergen, D. J. J. v., Domeier, M., Gaina, C., Tohver, E., Meert, J. G., McCausland, P. J. A., and Cocks, L. R. M., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, v. 114, p. 325-368.

Vincenz, S.A., Al-Khafaji, S., & Guja, N., 1967, Paleomagnetic Investigations of the Lamotte Formation, Missouri: Amer. Geophys. Union Transactions, 48(1), p. 84.

Wisniowiecki, M.J., & Van der Voo, R., 1981, Paleomagnetic results from the late Cambrian Bonne Terre and Lamotte Formations, SE Missouri: Eos, 62(17), 271.

Zartman, R., Brock, M., Heyl, A., & Thomas, H., 1967, K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United States. American Journal of Science, 265(10), 848-870.

Zijderveld, J. D. A., 1967, A.C. Demagnetization of rocks: Analysis of results, in Collison, D. E., K.M. Creer, and Runcorn, S. K., eds., Methods in Paleomagnetism: New York, El Sevier Science, p. 254-286.

Conclusion

Paleomagnetic and petrographic analyses of crystalline basement rocks and their overlying sedimentary cover indicate that paleoweathering processes can be recorded in erosional surfaces. However, the mechanism has several limiting factors: climate, paleotopography, and basement rock lithology can each enhance or limit the amount of hematite that can precipitate in the upper portions of the basement rock and record magnetic information.

The Vishnu granites and schists of southern Nevada contain Precambrian magnetizations in magnetite that were likely acquired soon after emplacement and metamorphism of the rocks. Although some specimens held stable magnetizations in hematite, unknown sedimentary history and a poorly constrained Proterozoic to Lower Cambrian apparent polar wander path make a definitive mechanism difficult to interpret for those magnetizations. Climatic conditions during the Cryogenian and Ediacaran, when the rocks were probably exposed, are also debated and therefore the results for the original hypothesis of hematite recording the time and extent of weathering are inconclusive in this portion of this work.

In Missouri, the low-permeability, weathering-resistant Grassy Mountain Ignimbrite likely provided some degree of protection for the underlying Butler Hill Granite and helped preserve the primary Proterozoic magnetization held in magnetite in the rocks. The Lamotte Sandstone contained a Devonian-Mississippian remagnetization that was likely acquired from hydrothermal activity during MVT-type ore-forming fluid movement. Paleotopographic relief in the basal

St. Francois aquifer could have directed fluid flow away from exposed portions of the Butler Hill Granite into paleotopographic lows, while the Grassy Mountain Ignimbrite provided protection for the underlying rocks. Some hematite likely containing Proterozoic magnetization was found in the Butler Hill Granite and could be indicative of supergene fluids penetrating the upper parts of the exposed granite where the Grassy Mountain Ignimbrite did not cover the unit or was eroded away.

A more thorough understanding of the Neoproterozoic APWP and tectonic forces during the Neoproterozoic is necessary to determine the significance of those magnetizations that yield Precambrian directions but do not correlate with established primary poles. In addition, more work on the Proterozoic sedimentary history of southern Nevada and the original extent of the Grassy Mountain Ignimbrite flows could shed light on coarser crystalline basement exposure during the time of proposed subaerial exposure. The characterization of paleoweathering surfaces using paleomagnetism can be a useful tool for paleoclimate modelling—however, more confidence can be placed in the method using more confined periods of geologic time when more is known about the arrangement of the continents and the earth’s magnetic field.